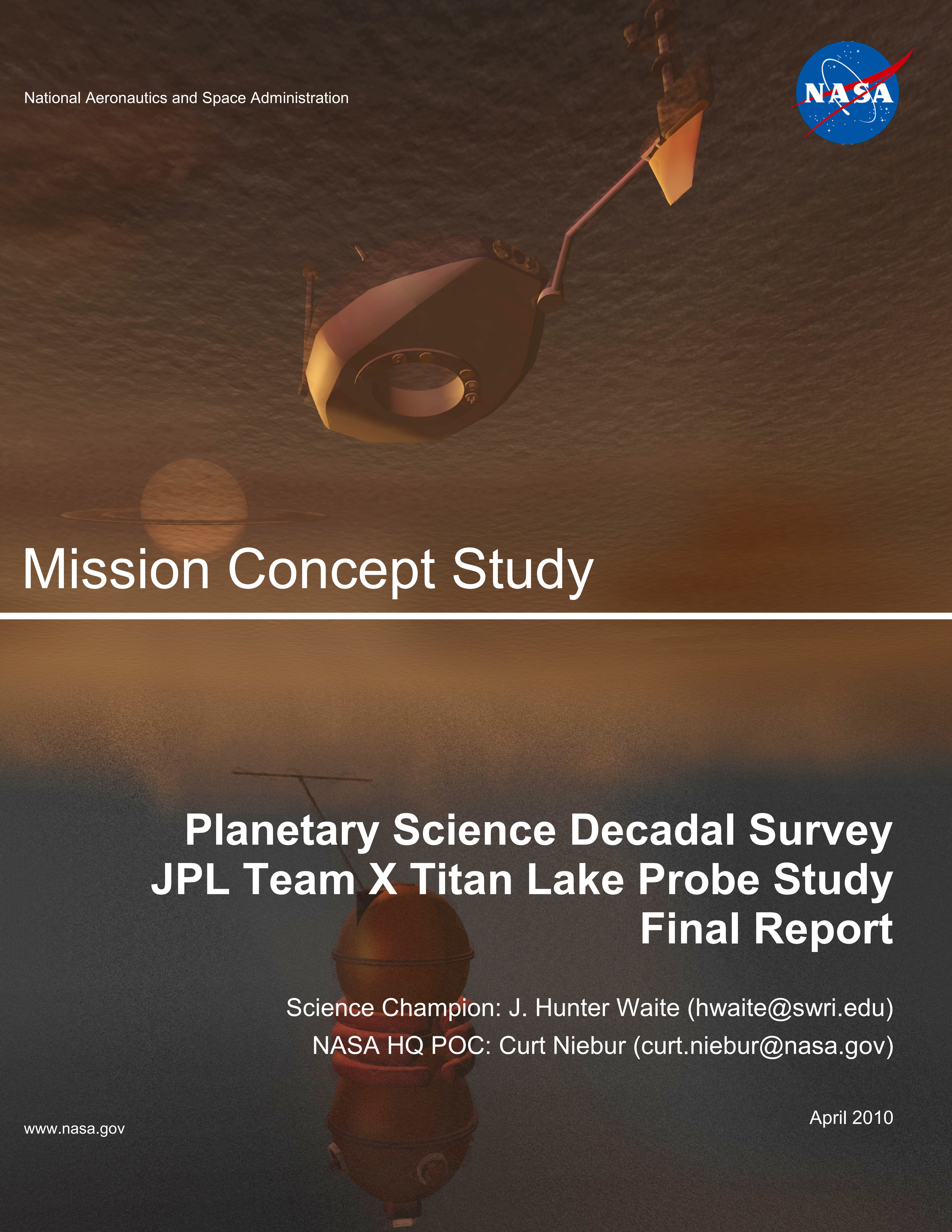


National Aeronautics and Space Administration

NASA

Mission Concept Study

Planetary Science Decadal Survey
JPL Team X Titan Lake Probe Study
Final Report

Science Champion: J. Hunter Waite (hwaite@swri.edu)

NASA HQ POC: Curt Niebur (curt.niebur@nasa.gov)

April 2010

www.nasa.gov

Data Release, Distribution, and Cost Interpretation Statements

This document is intended to support the SS2012 Planetary Science Decadal Survey.

The data contained in this document may not be modified in any way.

Cost estimates described or summarized in this document were generated as part of a preliminary concept study, are model-based, assume a JPL in-house build, and do not constitute a commitment on the part of JPL or Caltech. References to work months, work years, or FTEs generally combine multiple staff grades and experience levels.

Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

.

Planetary Science Decadal Survey

Mission Concept Study Final Report

Figures

Tables

Appendices

Study Participants

Role	Participant	Affiliation
Study Lead	John Elliot	Jet Propulsion Laboratory
NRC Panel Science Team		
Panel Lead	John Spencer	Southwest Research Institute
Science Champion	Hunter Waite	Southwest Research Institute
Science	Tom Spilker	Jet Propulsion Laboratory
Science	Zibi Turtle	Applied Physics Laboratory
Science	Caitlin Griffith	University of Arizona
Science	Chris McKay	Ames Research Center
Lander Study Team		
ACS	Bob Kinsey	Aerospace Corporation
CDH	Dwight Geer	Jet Propulsion Laboratory
EEIS/GSE	Joe Smith	Jet Propulsion Laboratory
Instruments	Tim Brockwell	Southwest Research Institute
Instruments	Luther Beegle	Jet Propulsion Laboratory
Instruments	Pat Beauchamp	Jet Propulsion Laboratory
Instruments	Peter Willis	Jet Propulsion Laboratory
Instruments	Rob Hodyss	Jet Propulsion Laboratory
Instruments	Peter Tsou	Jet Propulsion Laboratory
Landed Sys Config	Joe Melko	Jet Propulsion Laboratory
Mission Design	Nathan Strange	Jet Propulsion Laboratory
Planetary Protection	Andy Spry	Jet Propulsion Laboratory
Power	Paul Timmerman	Jet Propulsion Laboratory
Support SE	Jared Lang	Jet Propulsion Laboratory
Telecom	Michael Pugh	Jet Propulsion Laboratory
Thermal	Chris Paine	Jet Propulsion Laboratory
Advanced Project Design Team (Team X)		
Facilitator	Keith Warfield	Jet Propulsion Laboratory
ACS	Robert Kinsey	Southwest Research Institute
ACS	Ryan Lim	Jet Propulsion Laboratory
CDS	Dwight Geer	Jet Propulsion Laboratory
Configuration	Jamie Piacentine	Jet Propulsion Laboratory
Cost	Daniel Harvey	Aerospace Corporation
Deputy Systems Engineer	Mohammed Khan	Jet Propulsion Laboratory
EDL	Evgeniy Sklyanskiy	Jet Propulsion Laboratory
Ground Systems	Douglas Equils	Jet Propulsion Laboratory
Instruments	Marc Walch	Jet Propulsion Laboratory
Logistics	Melissa Vick	Jet Propulsion Laboratory
Mechanical	Matthew Spaulding	Jet Propulsion Laboratory
Mission Design	George Carlisle	Jet Propulsion Laboratory
Planetary Protection	Laura Newlin	Jet Propulsion Laboratory
Power	Keith Chin	Jet Propulsion Laboratory
Programmatics/Risk	Jairus Hihn	Jet Propulsion Laboratory
Propulsion	Masashi Mizukami	Jet Propulsion Laboratory

Role	Participant	Affiliation
Science	William Smythe	Jet Propulsion Laboratory
Software	Ashton Vaughs	Jet Propulsion Laboratory
Software	Harry Balian	Jet Propulsion Laboratory
Systems Engineer	Jared Lang	Jet Propulsion Laboratory
Telecom Systems	David Hansen	Jet Propulsion Laboratory
Telecom Systems	Michael Pugh	Jet Propulsion Laboratory
Thermal	Robert Miyake	Jet Propulsion Laboratory
JPL SS 2012 PSDS Lead	Kim Reh	Jet Propulsion Laboratory

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Executive Summary

This study focused on an in-situ examination of a hydrocarbon lake on the Saturnian moon Titan—a target that presents unique scientific opportunities as well as several unique engineering challenges (e.g., submersion systems and cryogenic sampling) to enable those measurements. Per direction from the National Research Council (NRC) 2012SS Planetary Decadal Survey Satellites Panel, and after an initial trade-space examination, study architectures focused on three possible New Frontiers–class missions and a more ambitious Flagship-class lander intended as a contributed portion of a larger collaborative mission.

The Flagship-class lander would include both a lake lander and a submersible probe. The New Frontiers–class mission options would include (1) a lake lander using a direct-to-Earth (DTE) communications link, (2) a submersible-only probe with a flyby relay spacecraft, and (3) a lake lander with a flyby relay spacecraft, respectively. All options would require advanced stirling radioisotope generators (ASRGs) to enable the missions, although the Flagship and DTE missions would carry the ASRGs on the lake landers, while the other two missions would carry the ASRGs on the flyby relay spacecraft. The latter missions would use batteries for the landed portion of the mission, which would limit the instrument suite and science return. The Flagship probe would carry a large suite of instruments capable of carrying out in-situ measurements of Titan's atmospheric evolution, lake-atmosphere hydrocarbon cycle, and pre-biotic lake chemistry, and of checking for the presence of a subsurface ocean. This list was reduced for the DTE mission, eliminating the submersible instrumentation as well as a few instruments on the lake lander. The submersible-only mission would carry just the GC-GC MS, lake properties package, and a Fourier transform IR spectrometer. Finally, the lake lander flyby mission would represent the science floor mission and would contain only the GC-GC MS and lake properties package. Lake landers for all architectures would be capable of sampling gases and liquids. In addition, both the Flagship and New Frontiers submersibles would be able to sample solids from the lake bottom as well as liquids.

Limitations on the current understanding of the Titan atmospheric and lake behaviors made landing in the small southern lakes less certain; all architectures assumed landings targeted at the much larger Kraken Mare in the north. This presented difficult trajectory constraints on the DTE mission since the likely New Frontiers launch opportunity left little time before Earth would no longer be in view from the lake surface. Consequently, a high C3 trajectory was required for this architecture to reduce travel time to Titan, increasing launch mass and launch costs.

Of the three New Frontiers–class missions, all exceeded the expected New Frontiers cost cap by enough to conclude that these designs would unlikely fit within this cost bin without modifications to the Decadal Survey Satellites Panel direction and the required study ground rules. All three missions would also require significant technology development in instrumentation, sample handling, and lake probe design, which would present issues in any future New Frontiers proposal competition.

1. Scientific Objectives

Science Questions and Objectives

The global methane cycle at Titan embodies both a short-term (years to thousands of years) hydrological and a long-term (millions of years to hundreds of millions of years) chemical transformation of methane to higher order organics. The Titan Lake Probe mission is designed to study the role of Titan's lakes in the global methane cycle—from both a hydrological and chemical transformation perspective. In the hydrological cycle, the lakes are tightly coupled to Titan's lower atmosphere, exchanging both methane and ethane in gas, liquid, and perhaps solid states. The role of the lakes in the longer chemical transformation cycle is less direct. In this case, the lakes serve both as a repository of accumulated "organic rain" from the upper atmosphere and a potential source of oxygen in the form of water due to the interaction of the lake with ice on the shore and lake bottom. This lake-based chemical transformation can significantly modify the chemistry creating many important pre-biological molecules. Furthermore, the lakes may sequester noble gases such as argon, krypton, and xenon that hold important clues about the outgassing of Titan's primary volatiles (molecular nitrogen and methane) over geological time.

The scientific objectives of the Titan Lake Probe mission are:

1. To understand the formation and evolution of Titan and its atmosphere through measurement of the composition of the target lake (e.g., Kraken Mare), with particular emphasis on the isotopic composition of dissolved minor species and on dissolved noble gases.
2. To study the lake-atmosphere interaction in order to determine the role of Titan's lakes in the methane cycle.
3. To study the target lake as a laboratory for both pre-biotic organic chemistry in water (or ammonia-enriched water) solutions and non-water solvents.
4. To understand if Titan has an interior ocean by measuring tidal changes in the level of the lake over the course of Titan's 16-day orbit.

Based on these science objectives, it is clear that an in-depth measurement of the lake composition, its exchange of gases with the atmosphere, and its interaction with solid and liquid material is of primary importance to the mission. The primary payload would be an analytical chemistry laboratory that includes hardware that can ingest samples of gas, liquid, and solids above, in, and below the lake feeding two capable mass spectrometers that determine the organic and isotopic composition of the sampled materials. The instrumentation would also include a meteorological package that can measure the rate of gas exchange between the lake and the atmosphere, and a lake-physical-characteristics package that would include pressure and temperature sensors as well as imaging sonar. Descent imaging on the way into the lake is important for defining the lake boundaries and thus enabling the determination of the diurnal lake tides. A simple visible or near-IR imager would be included for imaging any waves or floating material on the lake surface, and for imaging the shoreline if the spacecraft drifts to shore later in the mission. The imager is a fairly wide-angle system that does not require accurate pointing, and would be mounted on a short mast, with the ability to produce 360-degree panoramas once the spacecraft runs aground and no longer rotates freely. Imaging data return would be small; however, even an image or two per day would be valuable. The lake probe would include both a surface vehicle responsible for delivering the overall payload, assessing the near-lake meteorology, and providing communications, and a submersible vehicle that would characterize the physical and chemical characteristics as a function of depth, including sampling the solid sediments at the bottom of the lake.

The driving requirements for the mission are:

1. To land on, and preferably explore, the lake at depth while adequately communicating the data back to Earth via either direct-to-Earth (DTE) or relay communications. The sub-solar and sub-Earth points are in Titan's southern hemisphere from 2025 to 2038, and the largest lakes are near

the north pole. Therefore, it is specifically important to understand the feasibility of different mission architectures as a function of launch date.

2. To include a thermal design that allows sustained (>32 days) sampling of the 94 K lake environment.
3. To include a sample acquisition and handling system feeding the mass spectrometer inlet that allows representative sampling of gas, liquid, and solids from the 94 K lake environment.

Both the prior Titan Explorer (TE) and the prior Titan Saturn System Mission (TSSM) studies have demonstrated that it is possible to place a landing ellipse in the center of Kraken Mare or another one of Titan's large lakes from a range of trajectories, including Saturn flyby, Saturn orbital, or Titan orbital. Suggested mission concepts have included boats (TSSM) and submersible lake probes [1]. Both concepts allow first-order characterization of the lake composition and provide information about the lake-atmosphere interaction. These studies agree that a well-equipped chemical analysis system that includes noble gas, organics, and CHON isotopic determination are the first measurement priority and that a meteorological package that measures the relative humidity of methane and ethane, the static stability, the wind vector, the height of the boundary layer and other parameters relevant to modeling the evaporation from the lake, is a necessary secondary payload, as well as imaging sonar to determine the lake morphology and examine the diurnal tides.

Specific scientific measurements would include 1) determination of the lake's vertical structure (temperature and pressure), 2) determination of changes in lake composition and chemistry as a function of depth, 3) measurement of the lake tides from a fixed platform at the bottom of the lake, which in conjunction with (1) would allow determination of the Titan lake tides with an accuracy of ~10 cm (expected tidal range is ~1 m), and 4) characterization of the lake sediment composition. These additional objectives would require the payload to be augmented by a lake temperature and pressure sensor, as well as an upward-looking sonar.

Science Traceability

The overall relationship between the mission science goals, required measurements, instrumentation, and the subsequent mission constraints and requirements are summarized below in Table 1-1.

Table 1-1. Science Traceability Matrix

Mission Goals	Science Goals	Science Objectives	Science Investigations	Required Measurements / Determinations	Instrument
Goal A: How does Titan function as a system? To what extent are there similarities and differences with Earth and other solar system bodies?	**SGa:** To understand the formation and evolution of Titan and its atmosphere	**O4:** Characterize the atmospheric circulation and flow of energy	**I8:** Determine the effect of haze and clouds	**M14:** Extent and lateral and vertical distribution of clouds above the lakes	DISR, descent cameras, ASI, TDL
				M23: Determine the solar partitioning of energy	DISR, descent cameras
				M24: Measure the opacity structure of the atmosphere	DISR, descent cameras
				M25: Measure the vertical profile of particulates	Hi-res GC-GC MS
		O5: Characterize the amount of liquid on the Titan surface today	**I1:** Quantify the total major organic inventory present in the lakes and seas	**M1:** Separate methane, ethane, ethylene, acetylene, and hydrogen cyanide in the liquid mixture	Hi-res GC-GC MS
				M2: Bulk properties such as sound speed, density, refractive index, turbidity, thermal conductivity, permittivity	LPP, turbidimeter
			I2: Determine the depth of the lake at the landing site	**M4:** Measure the lake depth beneath the floating lander	Echo sounder
			I27: Determine the surface area of the lake	**M5:** Determine lake surface area from either descent imaging, orbiter imaging or existing data	DISR, descent cameras

Mission Goals	Science Goals	Science Objectives	Science Investigations	Required Measurements / Determinations	Instrument
Goal A: How does Titan function as a system? To what extent are there similarities and differences with Earth and other solar system bodies?	**SGa:** To understand the formation and evolution of Titan and its atmosphere	**O6:** Characterize the major processes transforming the surface throughout time	**I3:** Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events	**M6:** Map the distribution of different surface features around the landing site	DISR, descent cameras
		O8: Constrain the crustal expression of thermal evolution of Titan's interior	**I4:** Quantify exchange between interior and atmosphere	**M7:** Determine D/H in methane and ethane in the atmosphere and the lake	Low-res GC-GC MS
				M8: Determine noble gas isotopic ratios (Ar, Kr Xe)	Low-res GC-GC MS
	SGb: To study the lake-atmosphere interaction in order to determine the role of Titan's lakes in the methane cycle	**O3:** Characterize the major processes controlling the global distribution of atmospheric chemical constituents	**I1:** Quantify the total major organic inventory present in the lakes and seas	**M43:** Inventory organic content of the lakes, including potential solid species in suspension as a function of depth	Hi-res GC-GC MS, FTIR spectrometer, turbidimeter
			I7: Determine the atmospheric thermal and dynamical state	**M26:** Measure the wind speed above the lake	ASI-mast mounted
			I11: Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the lake boundary layer	**M43:** Inventory organic content of the lakes, including potential solid species in suspension as a function of depth	Hi-res GC-GC MS, FTIR spectrometer, turbidimeter
		O4: Characterize the atmospheric circulation and flow of energy	**I7:** Determine the atmospheric thermal and dynamical state	**M13:** Measure the surface temperature of the lake	LPP instrument
			I11: Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the lake boundary layer	**M18:** Wind directions at the surface of the lake	ASI-mast mounted
				M16: Determine the temperature gradients between liquid surface and surrounding terrains. Measure the pressure and temperature at the surface of the lake	ASI-mast mounted

Mission Goals	Science Goals	Science Objectives	Science Investigations	Required Measurements / Determinations	Instrument
Goal A: How does Titan function as a system? To what extent are there similarities and differences with Earth and other solar system bodies?	**SGb:** To study the lake-atmosphere interaction in order to determine the role of Titan's lakes in the methane cycle	**O4:** Characterize the atmospheric circulation and flow of energy	**I11:** Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the lake boundary layer	**M17:** Identify and quantify the molecules evaporating from the lake.	TDL-mast mounted
				M19: Quantify the liquid precipitating into the lake	TDL-mast mounted, hi-res GC-GC MS, FTIR spectrometer
				M22: Distribution of condensates at the surface	DISR, descent cameras, surface cameras, turbidimeter, FTIR spectrometer, hi-res GC-GC MS
				M23: Determine the solar partitioning of energy	DISR
				M31: Measure the temperature, pressure, speed of sound / refractive index and turbidity of the lake liquid	LPP, turbidimeter
	SGc: To study the target lake as a laboratory for pre-biotic organic chemistry in both water (or NH_3 enriched water) solutions and non-water solvents	**O2:** Characterize the relative importance of exogenic and endogenic oxygen sources	**I13:** Quantify the flux of endogenic oxygen from the surface and interior	**M28:** Isotopic ratio $^{18}O/^{16}O$	Low-res GC-GC MS
				M29: Nature and composition of O-bearing molecules	Hi-res GC-GC MS
	SGd: To understand if Titan has an interior ocean	**O7:** Determine the existence of a subsurface liquid water ocean and whether Titan has a metal core and an intrinsic magnetic field	**I14:** Determine the depth of the lake at the landing site over the course of Titan's 16-day orbit	**M30:** Measure the lake height above the submersible	Echo sounder
				M31: Measure the temperature, pressure, speed of sound / refractive index and turbidity of the lake liquid	LPP, turbidimeter
			I15: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M32:** Vector magnetic field measurements on the Titan surface to quantify the induced magnetic field and hence constrain the presence of a sub-surface conducting layer (possibly liquid water ocean)	Magnetometer

Mission Goals	Science Goals	Science Objectives	Science Investigations	Required Measurements / Determinations	Instrument
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**SGa:** To understand the formation and evolution of Titan and its atmosphere	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface	**I16:** Assay the speciation and abundance of atmospheric trace molecular constituents	**M33:** Detailed molecular analysis of the lake and atmosphere above the lake	Hi-res GC-GC MS, TDL-mast mounted, FTIR spectrometer
			I19: Determine the composition of organics in the lake and the isotopic ratios of major elements	**M36:** Mole fraction and isotopic ratio of C, N, and H in the organic molecules	Low-res GC-GC MS
	SGc: To study the target lake as a laboratory for pre-biotic organic chemistry in both water (or NH_3 enriched water) solutions and non-water solvents	**O10:** Characterize the degree to which the Titan organic inventory is different from known abiotic material in meteorites	**I24:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, and seas	**M43:** Inventory organic content of the lakes, including potential solid species in suspension as a function of depth	Hi-res GC-GC MS, turbidimeter, FTIR spectrometer
				M44: Determine optical and electrical properties of the liquid (transparency, refraction)	LPP
				M45: Determine optical properties of the lake materials to identify time dependent variations	LPP
			I25: Determine the chirality of organic molecules	**M46:** Chirality of complex organics	Hi-res GC-GC MS
		O11: Characterize what chemical modification of organics occurs at the surface	**I26:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics	**M47:** Search for complex oxygenated organics dissolved or in suspension	Hi-res GC-GC MS

2. High-Level Mission Concept

Overview

As part of NASA's support to the National Research Council (NRC) SS2012 Planetary Decadal Survey, the Jet Propulsion Laboratory (JPL) was assigned the task of developing several mission point designs aimed at in-situ science on and in one of the ethane/methane lakes of Saturn's moon Titan. Initial prioritized science requirements were supplied by the NRC Satellites Panel. The panel was specifically interested in a mission that would fit within NASA's New Frontiers proposal constraints and the landed portion of a larger Flagship mission. Architecture trade-space analyses as well as detailed point designs were to be performed by JPL. To meet this study's needs, the work was divided into two phases: (1) an initial examination of the architecture trade space and detailed point designs of the landed elements of the candidate architectures by a stand-alone study team; and (2) detailed designs and cost estimates of the total mission architectures by JPL's Advanced Projects Design Team (Team X). This arrangement allowed for a more free-ranging exploration of possible mission and landed element architectures by a team of specialists chosen for their relevant knowledge to the problem, while leveraging the efficiency and experience of Team X with the entry, descent, and landing (EDL) and spacecraft portions of the mission—areas routinely handled by this team. This work was done in close coordination with the Decadal Survey's Satellites Sub-panel with several panel members providing active guidance on the design process and decisions to JPL's two study teams.

The first phase of the study began in December 2009 and ran through January 2010. Two distinctly different objectives drove the two different mission categories. The design of the lake lander/submersible for the Flagship-sized mission focused on meeting, to the extent possible, the science requirements as supplied at the outset of the study by the panel, while the New Frontiers–sized missions were, to a greater extent, driven by the likely proposal cost constraint. Following the architecture trades, three initial architectures were selected to move on to point designs—a Flagship lake lander with submersible, which would be delivered by a Saturn or Titan orbiter spacecraft (not designed in the study) that would also provide data relay; a smaller lake lander with DTE communications capability and a Mars Exploration Rover (MER)-like "dumb" carrier stage; and a submersible-only probe with a flyby relay carrier spacecraft. Landed elements for these design points were developed in advance of, and delivered to, the Team X study (which was held on January 19–22) where the remainder of the mission designs were completed and the costs of the different designs estimated. Following the study, the supporting panel members reconsidered the designs and decided a lower cost option needed to be evaluated. This new minimum case (Option 4) was a floating lake lander with only three instruments and a flyby relay carrier spacecraft; this option was studied by Team X on February 4.

The study designs were all developed to the same set of assumptions and constraints. The first level of constraints were specified in the NASA-supplied *Ground Rules for Mission Concept Studies in Support of Planetary Decadal Survey* [2] document and included details on cost reserves, advanced stirling radioisotope generators (ASRG) performance and cost, Ka-band telecommunications usage, and launch vehicle costs—all of which were adhered to within the studies. The second level of constraints and assumptions were internal JPL best practices as specified in JPL documents *Design, Verification/Validation & Ops Principles for Flight Systems (Design Principles)* [3] and *Flight Project Practices* [4]. These documents covered margin and contingency levels as well as redundancy practices. Finally, since a primary goal of the study was to examine the compatibility of the different options with a possible future New Frontiers announcement of opportunity (AO) call, initial assumptions of a launch date sometime after January 1, 2021 and before December 31, 2023, and a complete mission cost cap of approximately $1B were also assumed. The latter assumption came from adjusting the cost cap on this latest New Frontiers AO for differences between that AO's cost assumptions and the currently specified Decadal Survey assumptions. It should be viewed as an approximation as the eventual cost cap and cost estimates that slightly exceed it should not be discounted as possible New Frontiers–class missions.

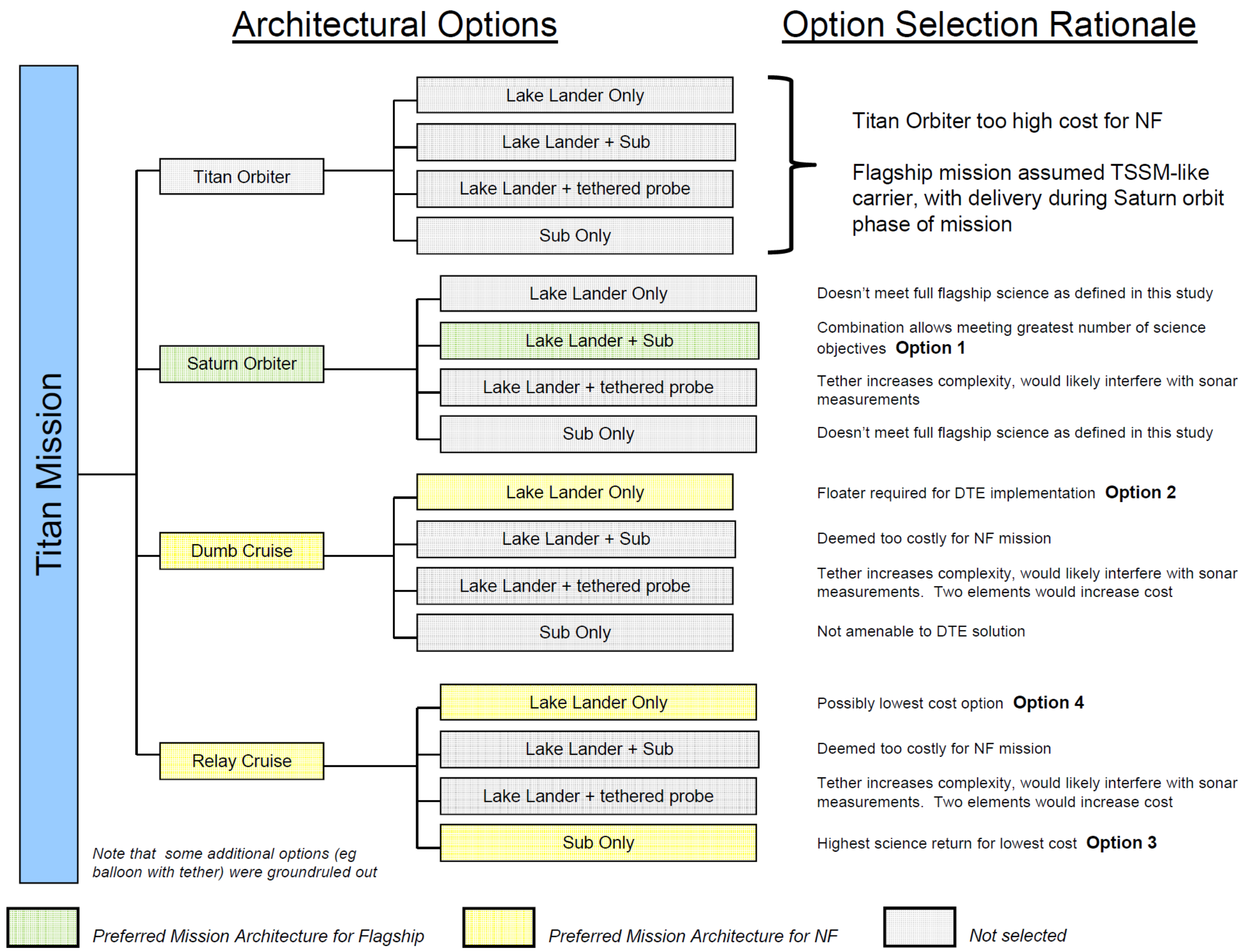


Figure 2-1. Architecture Trade Tree

Key trades that eventually led to the final point designs are described in detail later in this section and descriptions of the final designs are included in Section 3.0. Briefly, the architectures identified for detailed point designs and cost estimates and their selection rationale are provided here and are shown graphically in Figure 2-1. Each of the following four mission options were also measured against their intrinsic scientific value in terms of how well each option addressed the science goals outlined in the science traceability matrix. A numerical value was given to each option by assigning the following maximum values to each of the science subgoals: A—10 points, B—7.5 points, C—5.0 points, and D—2.5 points, i.e.,

- Subgoal A (10 points): To understand Titan via measurement of the composition of the lake
- Subgoal B (7.5 points): To study the lake-atmosphere interaction
- Subgoal C (5 points): To study the lake as a laboratory for pre-biotic organic chemistry
- Subgoal D (2.5 points): To understand if Titan has an interior ocean

Option 1: Flagship Mission (Scientific Value: 25/25)—This configuration was considered as a US contribution to a possible international mission. The lake lander would represent a major portion of the mission's science return, but it would not be the only science. The most likely Flagship configuration would involve a carrier/relay spacecraft in Saturn orbit carrying out other science investigations throughout the Saturnian system (much like the TSSM proposal). As such, the Titan-landed portion of a major venture to Saturn would need to carry out an extensive lake investigation to advance beyond Cassini and to justify inclusion. Accordingly, the lake lander, submersible, and the 32-day mission were all

viewed as necessary to advance the Titan in-situ science in all four investigation areas (atmospheric evolution, atmosphere-lake interaction, lake chemistry, and interior structure) described in the prior Scientific Objectives section. The extensive payload on the floating lander, 32 days of operations, and limited link opportunities with the Saturn-orbiting relay spacecraft made the use of ASRGs more attractive than the battery alternative. Some consideration also went into the question of how to handle the probe data retrieval. A tethered probe was considered but dismissed because the drifting floating lander would likely drag the submersible and interfere with the lake depth measurements needed for Titan interior science. Lake lander VHF data relay was also considered but this too would also be limited by the drifting lake lander. A submersible that could transmit data to the floating lander while in range then resurface at the end of the 32-day mission to transmit directly to the relay spacecraft was the final adopted architecture. The mission would launch around 2025 and would reach the Kraken Mare landing site after sunset, but this was not seen as an issue since the carrying spacecraft would provide the data downlink.

NOTE: This design point was not a complete mission, but select components of a larger mission; therefore, there is no end-to-end design or estimate and it cannot be directly compared to the other options. Furthermore, the lack of complete design information would preclude its inclusion in the NRC's planned independent cost estimate. The participating panel members were aware of this limitation, but instructed that it be included in the study along with the other options.

Option 2: New Frontiers Floating Lander with DTE Communications (Scientific Value: 20/25)—As previously stated, this option would consist of a floating lake lander with a DTE communication capability that would be carried to Titan by a simple carrier stage, which would rely on the lander for much of its avionics and would have no function once the lander is released. The removal of the submersible and several instruments eliminated the interior structure objective and reduced the achievable science in the other three focus areas. DTE link requirements drove the decision to use ASRG power on the lander as well as the decision to communicate at X-band (atmospheric attenuation at Ka-band). The DTE requirement coupled with the New Frontiers launch date (2022) also drove the mission to a six-year cruise, which then drove the use of a large bi-prop system on the carrier, putting the mission on the largest and most expensive Atlas V launch vehicle. This option exceeded the assumed New Frontiers cost cap by more than $500M and was not considered a viable candidate as a future New Frontiers proposal concept.

Option 3: New Frontiers Submersible with Relay Communication (Scientific Value: 21/25)—The third option would not require DTE and could be accommodated with a much smaller launch vehicle and a little over a nine-year cruise phase (assuming a similar launch date as the second design option). This mission would consist of a single submersible probe that would briefly float on the lake's surface while making surface measurements, then submerge and conduct measurements at depth, and finally resurface the part of the probe containing the telecom and data storage subsystems two days later to transmit its collected data to the flyby relay carrier spacecraft before moving out of range. In the interest of reducing cost, the instrument payload was further reduced to a two-dimensional gas chromatograph mass spectrometer (GC-GC MS), Fourier transform infrared (FTIR) spectrometer, lake properties instruments, and a descent camera; and the science largely became focused on just two areas: atmospheric evolution and lake chemistry. This option also exceeded the New Frontiers cost cap by approximately $500M and was not considered a viable candidate as a future New Frontiers proposal concept.

Option 4: New Frontiers Floating lander with Relay Communication (Scientific Value: 16/25)—Following Option 3, the panel members felt that the studies had not yet reached the true minimum mission and one more design point study was needed to capture this limiting case. The fourth and final option examined was a floating probe carrying only three instruments and a flyby carrier/relay spacecraft. Surface operations would be reduced to 12 hours. The mission trajectory design would be similar to that of Option 3, but probe release would only be two months before entry (three months in Option 3) since the spacecraft would only need to stay within link distance for 12 hours. The instrumentation would be further reduced to a GC-GC MS, lake properties instruments, and a descent camera. The flyby spacecraft would be identical to the spacecraft used in Option 3. This option also exceeded the expected New Frontiers cost cap by approximately $400M and was not considered a viable candidate as a future New Frontiers proposal concept.

All of the options examined were significantly more expensive than the likely New Frontiers cost limit, but all were also significantly less than past Outer Planets Flagship Missions. The technology development required for a lake lander mission is also more extensive than what has been required for the two current New Frontiers missions (JUNO and New Horizons). While the three options examined do not constitute all possible approaches to achieving in-situ lake science at Titan, they do illustrate the unique challenges presented by this target and suggest that a funding level greater than New Frontiers would be required to achieve this objective.

Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). Following the completion of this study, the four options presented in this report are at CML 4. An initial CML 3 trade-space analysis was completed by a dedicated study team at the outset of this work. The initial architectural trade space was culled down to four likely architectures during this first phase of this study; each option was then defined at the assembly level and was estimated for mass, power, data volume, link rate, and cost by Team X using JPL's institutionally endorsed design and cost tools. Risks were also compiled as part of this study.

Table 2-1. Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Technology Maturity

The new enabling technologies are those required to develop and mature the in-situ instruments. In some cases, instruments used in terrestrial applications could be adapted for use on Titan; in other cases, instruments specific to this particular mission are in development. Table 4-2 in the Technology Development Plan section shows a list of those required instruments and their current technology readiness levels (TRLs), with an estimated cost to develop the instrument system to TRL 6. Flight qualification would occur during Phase A, which would take two years. The rough order of magnitude (ROM) cost of this qualification is provided in column four. The critical aspects in the development of the specific instruments, as well as the heritage and state of development, are provided in the last column.

Note that the three lowest TRL-level technologies are associated with the sample acquisition and handling system and the echo sounder. For the first two (a sample handling system for the floating lander and another system for the submersible), methods need to be developed to ingest the liquid methane/ethane so that the chemical analyses can be performed by the GC-GC MS. Such methods exist to sample ocean waters and sediments on Earth, but would need to be redesigned to acquire the cryogenic fluids on Titan, with particular attention given to the materials used. The mass spectrometers and GC-GC instruments have been developed to the brassboard stage, but the instrument system, including valves and plumbing need engineering to reach the prototype stage. All the instruments need

testing in the expected lake environment, which should be relatively stable inside the thermal enclosure. Most of the GC-GC MS and FTIR instruments also require mass and power reductions.

Key Trades

Key Architecture Trades

Submersible Data Retrieval—Option 1 considered a number of methods for "through-the-liquid" telecom to evaluate whether the submersible could transmit all its data to the floating lander for relay, eliminating the need to resurface. While the VHF system incorporated in the design would allow communication for the lake descent phase and early operations of the submersible, its relatively limited range was determined insufficient to be relied upon, given the probable drift of the floating lander over the 32-day mission length. The limited range of the submersible's VHF transmitter necessitated the resurfacing of the submersible for direct communications with the orbiting spacecraft, which added operational complexity to the mission and technical complexity to both the submersible (resurfacing capability) and the carrier spacecraft (VHF receiver).

Tethered Submersible—Use of a tethered submersible was an early trade in Option 1. The tethered architecture was considered incompatible with the need for the submersible to remain stationary for the 32-day sonar tidal measurement period, since it was determined to be likely that the drifting floating lander would tend to drag a tethered submersible with it.

DTE Lander Architecture Trades—The DTE lander mission architecture is shaped by the need to have Earth in view during lake operations for DTE communications. Likely New Frontiers launch dates (2021–2023, with a target for the study of 2022) require more than 2200 kg of propellant to reach Kraken Mare before sunset. Other targets (e.g., Ontario Lacus in the southern hemisphere) were assessed, but were found to be smaller than the predicted landing ellipse, raising the possibility of missing the target lake to a significant level, and making them unsuitable as possible landing sites. The large bi-prop system required to reach Kraken Mare in time for a lander DTE telecom link drives the spacecraft size, the launch vehicle selection, and the cost.

Lander Phased-Array Antenna vs. Articulated High-Gain Antenna (HGA)—Option 2 considered the use of a phased-array antenna for DTE communication, traded against the articulated HGA. Performance of the phased-array antenna was found to be inadequate in this application and the articulated HGA, using a beacon from Earth, was chosen for this option.

Operation Mode Durations vs. Power—Power limitations required some adjustment to operations in cruise and safe modes. Normally, the telecom system would be fully powered in both modes but the transmitter draws considerable power and pushed the total spacecraft power beyond the output of two ASRGs. Team X opted to leave the receiver on, but turn off the transmitter during these modes to conserve power. Periodically, a command to turn the transmitter on could be sent and engineering data retrieved when needed.

Cruise/Relay Solar vs. ASRG Power—Use of solar power for the cruise/relay stages in Options 3 and 4 in lieu of ASRGs was briefly assessed. It was determined that the unknown costs of developing an array of sufficient size and low intensity, low temperature (LILT) characteristics to be of use could potentially increase cost. ASRGs were chosen as the lower risk alternative.

Future Trades

One trade that could be looked at in a future study is the use of solar power on the flyby carrier/relay spacecraft in Options 3 and 4. ASRGs were assumed to be the low mass/low cost option and more likely to fit within the New Frontiers cost constraints. Additionally, there was some concern about the attitude control issues, technology development issues, and operational constraints that would likely arise with the large solar arrays, but there was no definitive examination of this alternate power option and no cost estimate.

3. Technical Overview

Several other studies have examined the concept of placing a floating lander element on the lakes observed at Titan. The prior TE and TSSM Flagship studies used a fully implemented payload to explore the lakes of Titan, as well as the lake-atmospheric interactions that are important to understanding Titan's methane cycle.

Instrument Payload Description

The instruments described below are used to constitute payloads for four different options—a relay orbiter with both a boat (floating lander) and a submersible (sinker), a floating lander with DTE communications, a sinker with relay communications, and a floating lander with relay communications. The number of instrument teams decreases with increasing option number—both through reduction in the number of sensors and repackaging of the remaining sensors.

The primary experiment, as noted in the Science Objectives section, is compositional measurements utilizing a high-capability mass spectrometry system. This system includes gas chromatography × gas chromatography to provide two-dimensional separation of organic compounds feeding 1) a high-resolution mass spectrometer to provide exact mass determination and 2) a conversion oven network coupled to a small dedicated isotope ratio mass spectrometer for compound specific C, H, O, and N isotopic analysis.

Most of the instruments have high conceptual heritage (i.e., something similar has flown) but low actual flight heritage, as would be expected for the availability of in-situ instruments that are deployed in a lake at temperature below 100 K. Anticipated challenges include sealing windows; transfer of cryogenic samples to sampling ports, excluding large particles from the sampling ports; and meeting the mass and power targets for the instruments. The instruments are designed to work in a protected environment (with the possible exception of the cameras, which are already qualified to operate at Mars night time temperatures). The sampling system must accommodate the sample transition from ambient conditions to the analysis environment. A technology development program to retire risks associated with this in-situ instrument suite would lower the overall risks to this mission.

A detailed operational timeline developed for this mission (not included in this report) demonstrates that this instrument suite works well together for all options (with respect to power and data rate). The sampling rates and data return are sufficient to meet the science objectives shown in the science traceability matrix (Table 1-1).

Table 3-1 provides the specifications for all instruments described below.

- The hi-res GC-GC MS system would carry out detailed chemical analysis of the atmospheric species as well as the constituents of the lake. This system would include gas chromatography × gas chromatography to provide two-dimensional separation of organic compounds feeding 1) a high-resolution mass spectrometer to provide exact mass determination and 2) a conversion oven network coupled to a small dedicated isotope ratio mass spectrometer for compound specific C, H, O, and N isotopic analysis. The hi-res GC-GS MS has a mass range of up to 1,000 Da and a resolution of over 10,000. This instrument would be able to identify complex solid material collected from the lake bed as part of the submersible. It is notionally based upon a design proposed by Hunter Waite for the Mars Science Laboratory (MSL) project.
- The lake properties package (LPP) instrument would measure the properties of the lake, including liquid pressure, temperature, reflective index, speed of sound, and permittivity meter. This instrument was based upon a similar instrument that flew on the Huygens probe. Two slightly different versions of this instrument would be required, depending on if it was used on a floating or a submersible platform. This instrument would require calibrations both on the ground pre-flight and during flight.

- The echo sounder would measure the depth of the lake as the submersible descends and after the vehicle reaches the lake bottom. This instrument design was based upon echo sounders used in terrestrial ocean environments. Some work would have to be performed to identify the optimum frequency that the echo sounder would use.
- The turbidimeter would measure lake current movements from the submersible vehicle by studying suspended particles inside the liquid. It uses a light source and an off-axis detector to measure scattered light. This instrument was notionally based upon the nephelometer that was part of the Galileo Probe.
- The relative humidity instrument would be mounted on a mast at three different heights measuring the relative humidity at these three levels. This instrument was based upon a hybrid design that incorporated engineering data from the tunable diode laser (TDL) sensors that flew on the Mars Polar Lander and the tunable laser spectrometer (TLS) sensors that are part of the MSL payload. The TDL sensors would most likely require a calibrating channel, in which a known gas could be analyzed for temperature and pressure effects.
- The atmospheric structure instrument (ASI) would be mounted on a mast at three different heights measuring the atmospheric structure, including pressure and temperature, at these three levels. This instrument was based upon several that have flown, including on the Phoenix and pathfinder Mars missions, as well as the Huygens probe. This instrument could be calibrated through inclusion of a fourth channel that exists within the warm electronics box (WEB).
- The descent instrument would take measurements of the atmosphere during descent, and would be composed of a suite of small instruments, including a violet photometer, visible spectrometer, infrared (IR) spectrometer, solar aureole, and sun sensor. This instrument was based upon the descent imager–spectral radiometer (DISR) instrument that was part of the Huygens probe package. It would identify the total radiative flux incident on the lakes and would allow a better model to understand methane and hydrocarbon transport from the liquid reservoirs to the atmosphere.
- The surface cameras would take panoramic images at the surface at 3 × 120° and -80° to +40° elevations. These cameras were preliminarily based upon the MER cameras, which have seen over 40 built. The extra increase in mass represents structure, heaters, and other hardware to ensure operations on Titan.
- The magnetometer would measure the magnetic fields. This instrument would return data on field strength of the intrinsic magnetic fields on Titan.
- The low-res GC-GC MS instrument would carry out detailed chemical analysis of both the atmospheric species as well as the constituents of the lake. The mass range is up to 1000 Da, with a resolution of over 1000. It would be able to identify complex solid material collected from the lake bed as part of the submersible. Like the high-res GC-GC MS, it is notionally based upon a design that was proposed by Hunter Waite for MSL. The design for both instruments is nearly identical, and for a Flagship mission where two instruments would be required, some economies of scale could be counted on to ensure some substantial cost savings. Calibration of this instrument would require the carrying of a cache of known gas, which could be introduced into the GC-GC MS upon landing. In addition, a solid sample that could be pyrolized, in much the same way that the organic blank on MSL will operate, would be required for use on the bottom of the lake.
- The FTIR spectrometer instrument would make IR spectral measurements of the lake material as a function of depth during descent to the lake bottom. This instrument was largely notional since no in-situ FTIR has flown. Some of the technical data was obtained from Robert Carlson, who proposed an FTIR as part of the MSL payload. This instrument would return FTIR spectra from ~2.5 to 25 microns throughout the lake descent. In addition, once on the bottom, it would analyze the solid material at the bottom, returning a vertical profile of the lakes composition.
- The descent cameras would take images during descent at 60º down and horizontal views. These cameras were based upon the MER cameras, and would operate within the WEB, and thus were assumed to be in a controlled environment behind windows.

Table 3-1. Instrument Specifications

Item	Units	Hi-Res GC-GC MS	LPP Instrument	Echo Sounder	Turbidimeter	Relative Humidity (TDL-Mast Mounted)	Atmospheric Structure Instrument (ASI-Mast Mounted)	Descent Instrument (DISR)	Surface Cameras	Magnetometer	Low-Res GC-GC MS	FTIR Spectrometer	Descent Cameras
Volume of the instrument	cm^3	33,000	785	250	200	204	47,235	396	480	200	33,000	–	320
Instrument mass **without** contingency (CBE*)	kg	25.0	4.0	5.0	2.0	6	4.53	8	1.4	5	25.0	2	0.6
Instrument mass contingency	%	30	30	30	30	30%	30%	30	30	30	30	30	30
Instrument mass **with** contingency (CBE+Reserve)	kg	32.5	5.2	6.5	2.6	7.8	5.9	10.4	1.8	6.5	32.5	2.6	0.8
Instrument average payload power **without** contingency	W	150	10	5	10	30	6.75	11	13	2	150	10	22
Instrument average payload power contingency	%	30	30	30	30	30%	30%	30	30	30	30	30	30
Instrument average payload power **with** contingency	W	195	13	6.5	13	39	8.8	14.3	16.9	2.6	195	13	28.5
Instrument average science data rate^ **without** contingency	kbps	1,000	100	0.1	0.1	100	1	100	1,000	10	1,000	10	1,000
Instrument average science data^ rate contingency	%	30	30	30	30	30	30%	30	30	30	30	30	30
Instrument average science data^ rate **with** contingency	kbps	1,300	130	0.13	0.13	130	1.3	130	1,300	13	1,300	13	1,300
Type of data		This instrument returns complex mass spectra, which includes retention times so that functional analysis can be made.	–	–	–	–	–	–	–	–	–	–	–
Number of measurements per TDL		–	–	–	–	576,671	–	–	–	–	–	–	–
Instrument fields of view for each camera (if appropriate)		–	–	–	–	–	–	–	120	–	–	–	60º down
Number of images taken		–	–	–	–	–	–	–	96	–	–	–	5 (for full panorama)
Number of pings for Flagship mission		–	–	384	–	–	–	–	–	–	–	–	–
Total data volume		–	–	12.0 per ping	–	–	–	61,647.840 per descent	301,823	2,916.421	–	59,040 (for 2 km descent)	31,460.000 per full panorama (two will be taken for Flagship mission)
Maximum data volume per sample	kbits	4,801,613	67	–	–	88,259	100	–	–	–	–	–	–

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Payload Options

This study examined four payloads, each with descending complexity (Tables 3-2 through 3-5). In order to assess the scientific return for each payload configuration, the following numerical values were assigned to each of the four mission science goals: Goal A—10 points, Goal B—7.5 points, Goal C—5 points, and Goal D—2.5 points, giving rise to a maximum science return of 25 points. The first payload was designed for a complete Flagship mission to study the Titan lakes and their interaction with the atmosphere, with a full science return of 25/25. It consists of a floating lander that determines the physical state of the atmosphere and performs a depth profile of the physical and chemical components of the lake at regular intervals until the submersible reaches the bottom of the lake. Figure 3-1 provides a graphical representation of the mission duration.

Option 1: Flagship Mission (Science Return: 25/25)

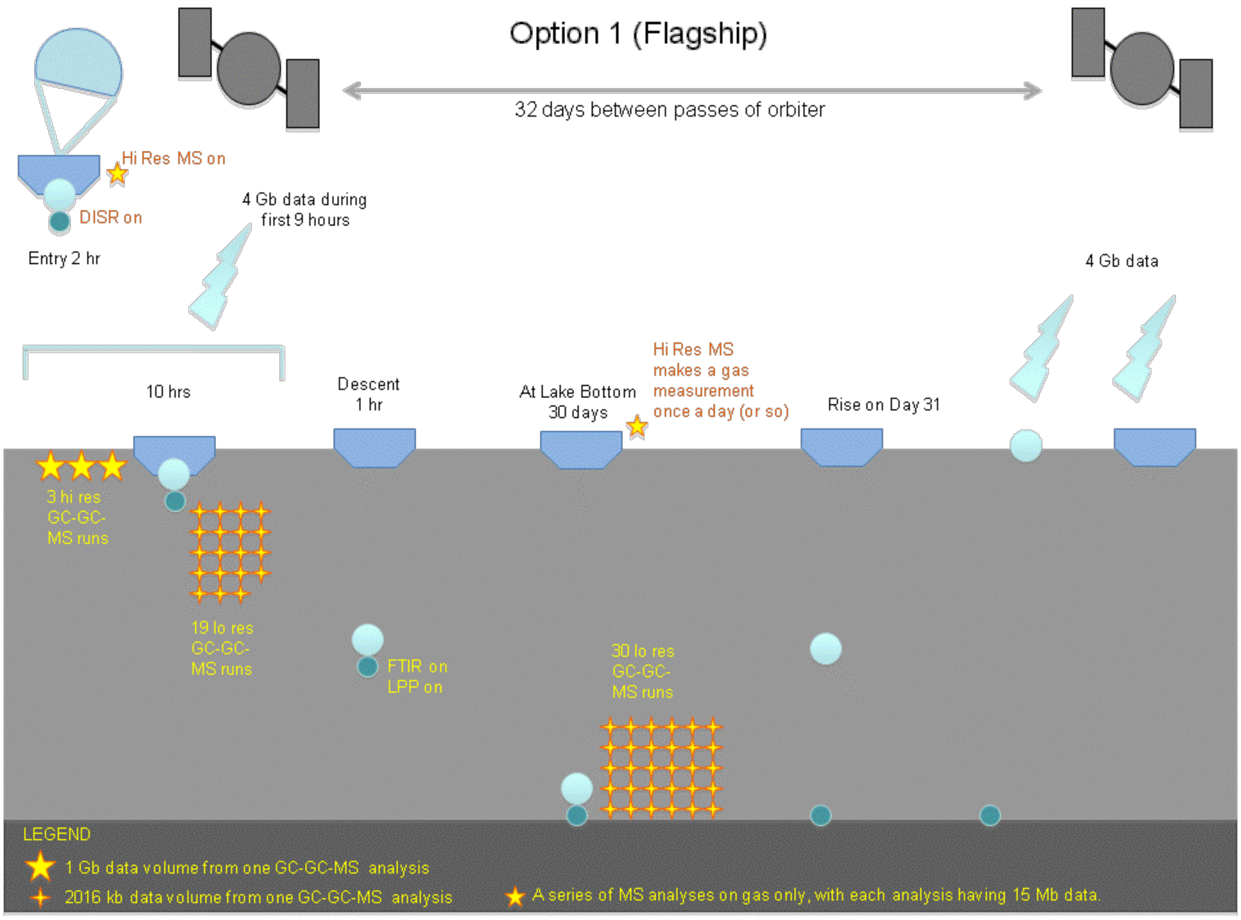


Figure 3-1. Mission Duration—Option 1

Table 3-2. Payload Mass and Power—Option 1

	Mass			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Floating Lander Instrument Suite	**62.9**	**30%**	**81.8**	**267.7**	**30%**	**348.0**
High-res GC-GC MS	25.0	30%	32.5	150	30%	195
Rain gauge	0.1	30%	0.13	-	30%	-
Surface cameras (3 individual units)	1.4 (each)	30%	5.5 (total)	13	30%	16.9
Decent cameras (two camera)	0.6	30%	0.8	11	30%	14.3
Turbidimeter	2.0	30%	2.6	10	30%	13
Echo sounder	5.0	30%	6.5	5	30%	6.5
Magnetometer	5.0	30%	6.5	2	30%	2.6
LPP instruments	4.0	30%	5.2	10	30%	13
(Mast) relative humidity (TDL) (3 individual units)	2.0 (each)	30%	7.8 (total)	30	30%	39
(Mast) wind speed / pressure / temperature (3 individual units)	1.0 (each)	30%	3.9	6.7	30%	8.8
DISR (violet photometer, visible spectrometer, IR spectrometer, solar aureole, sun sensor)	8.0	30%	10.4	30	30%	39
Submersible Instrument Suite	**38**	**30%**	**49.4**	**185**	**30%**	**240.5**
Low-res GC-GC MS	25.0	30%	32.5	150	30%	195
FTIR spectrometer	2.0	30%	2.6	10	30%	13
Echo sounder	5.0	30%	6.5	5	30%	6.5
Turbidimeter	2.0	30%	2.6	10	30%	13
LPP instruments	4.0	30%	5.2	10	30%	13
Total Payload Accommodations	**100.9**	**30%**	**131.2**	**452.7**	**30%**	**588.5**

The next three payload options were designed to put together a New Frontiers payload that could partially answer some of the questions posed in the science traceability matrix (Table 1-1). Different mission scenarios are graphically represented for each payload (Figures 3-2 through 3-4).

Option 2: New Frontiers Floating Lander with DTE Communications (Science Return: 20/25)

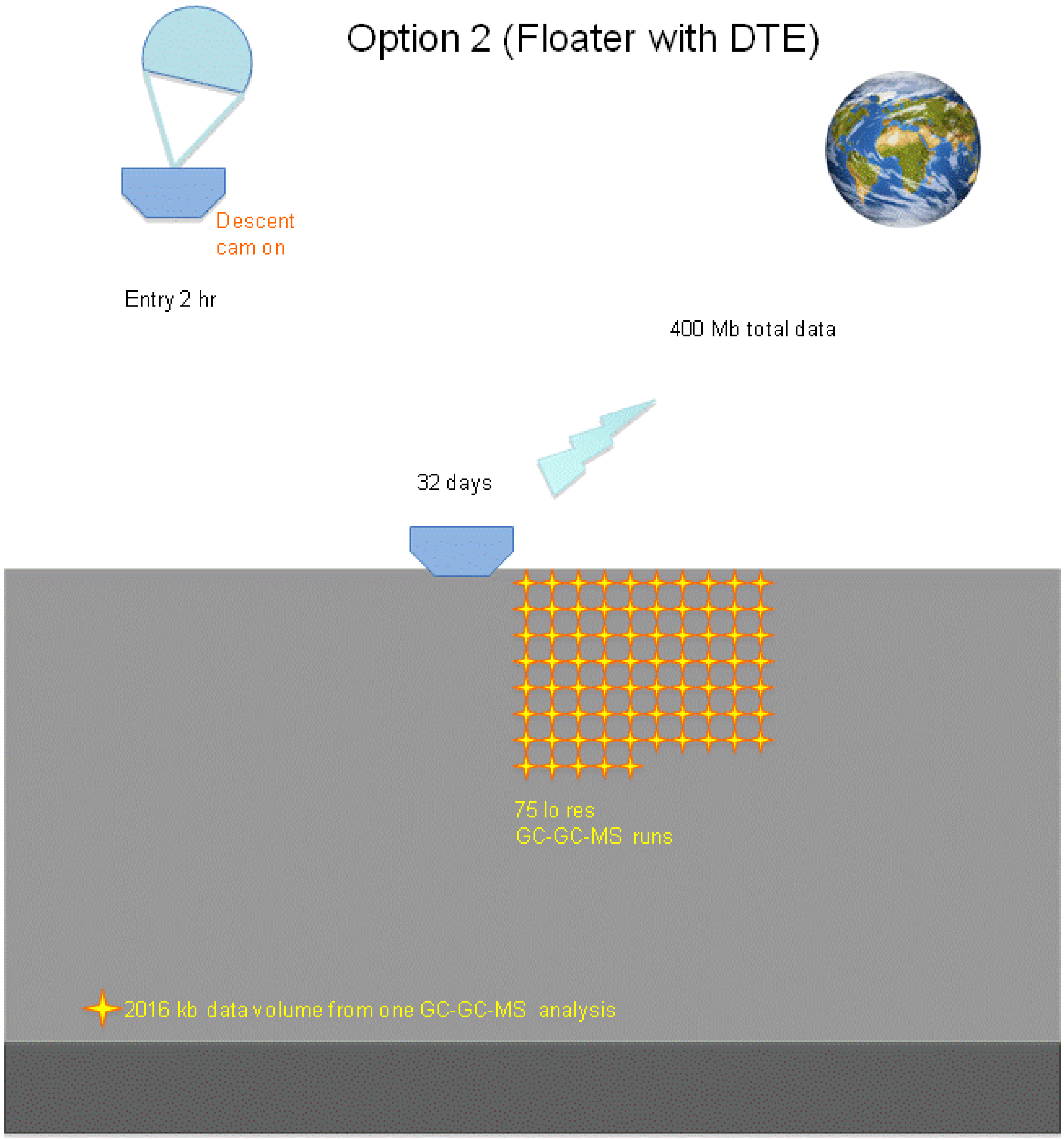


Figure 3-2. Mission Duration—Option 2

Table 3-3. Payload Mass and Power—Option 2

	Mass			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Floating Lander Instrument Suite						
Low-res GC-GC MS	25.0	30%	32.5	150	30%	195
Rain gauge	0.1	30%	0.13	-	30%	-
Surface cameras (3 individual units)	1.4 (each)	30%	5.46 (total)	13	30%	16.9
Descent cameras (2 individual units)	0.3 (each)	30%	0.78 (total)	11	30%	14.3
Turbidimeter	2.0	30%	2.6	10	30%	13
Echo sounder	5.0	30%	6.5	5	30%	6.5
LPP instruments	4.0	30%	5.2	10	30%	13
(Mast) wind speed / pressure / Temperature (3 individual units)	1.0 (each)	30%	3.9 (total)	6.7	30%	8.8
(Mast) relative humidity (3 individual units)	2.0 (each)	30%	7.8 (total)	30	30%	39
Descent instruments (violet photometer, visible spectrometer, IR spectrometer, solar aureole, sun sensor)	8.0	30%	10.4	30	30%	39
Total Payload Accommodations	**57.9**	**30%**	**75.3**	**265.7**	**30%**	**345.5**

Option 3: New Frontiers Submersible with Relay Communication (Science Return: 21/25)

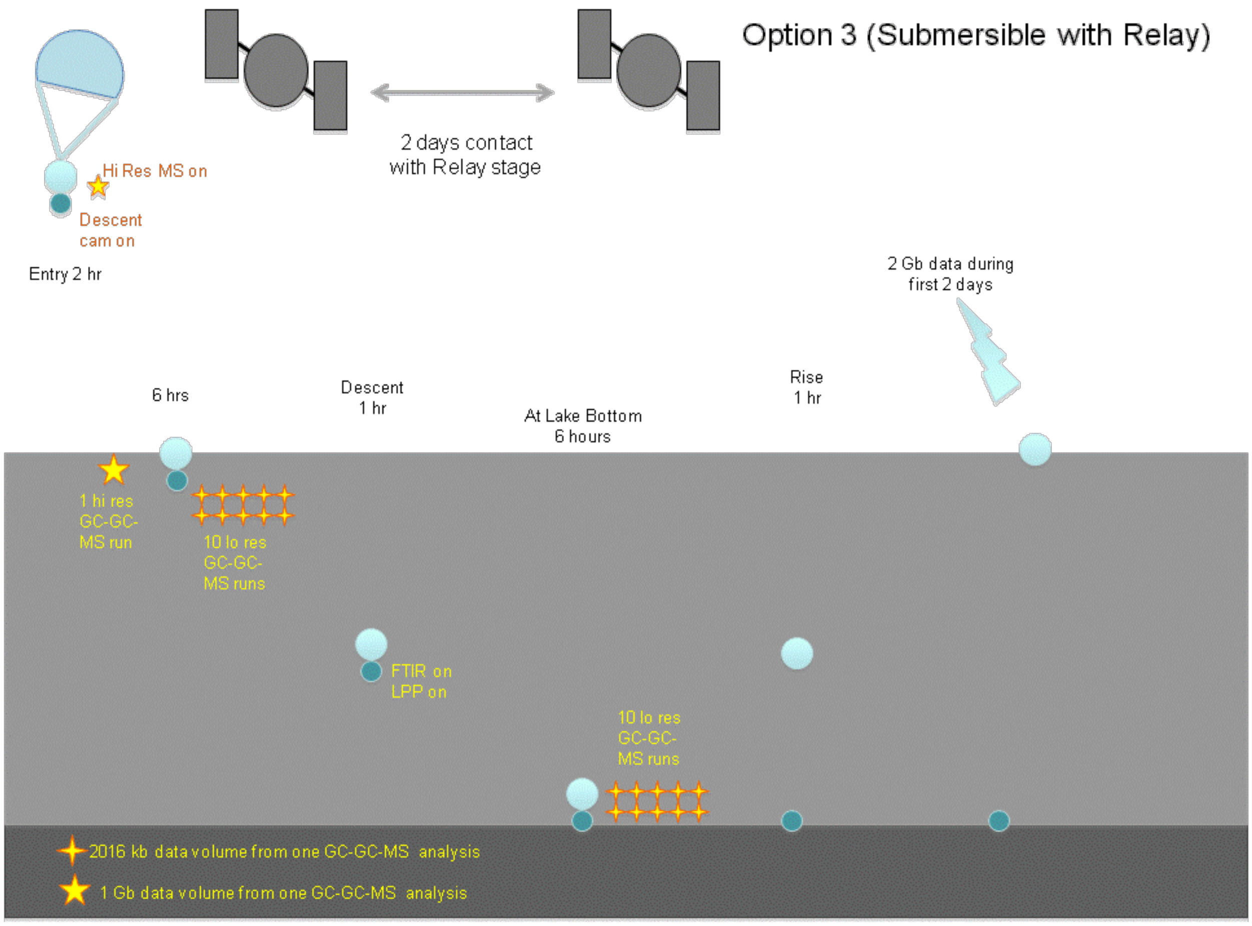


Figure 3-3. Mission Duration—Option 3

Table 3-4. Payload Mass and Power—Option 3

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Submersible Instrument Suite						
Hi-res GC-GC MS	25.0	30%	32.5	150	30%	195
FTIR spectrometer	2.0	30%	2.6	10	30%	13
LPP instruments	4.0	30%	5.2	10	30%	13
Descent camera	0.3	30%	0.4	22	30%	28.6
Total Payload Accommodations	**31.3**	**30%**	**40.7**	**192**	**30%**	**249.6**

Option 4: New Frontiers Floating lander with Relay Communication (Science Return: 16/25)

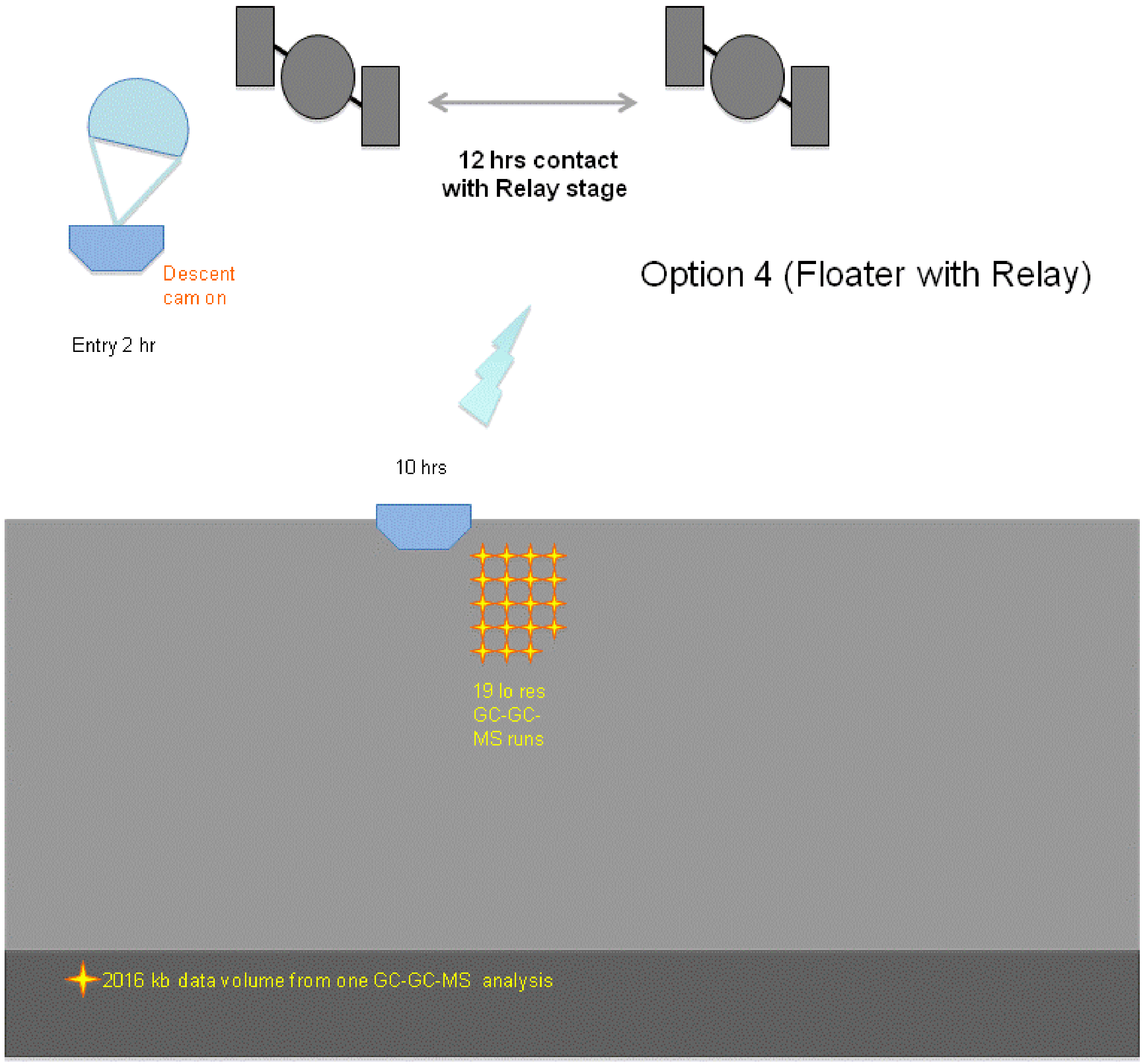


Figure 3-4. Mission Duration—Option 4

Table 3-5. Payload Mass and Power—Option 4

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Submersible Instrument Suite						
Low-res GC-GC MS	25.0	30%	32.5	150	30%	195
LPP instruments	4.0	30%	5.2	10	30%	13
Descent camera	0.3	30%	0.4	22	30%	28.6
Total Payload Accommodations	**29.3**	**30%**	**38.1**	**182**	**30%**	**236.6**

Flight System

The following sections describe the flight systems for the four options studied. The Flagship architecture would include two in-situ elements—a floating lander and a submersible—packaged together in a single aeroshell and delivered to Titan from Saturn orbit by a Flagship-class carrier spacecraft (not designed as part of this study). The New Frontiers options all include a single in-situ element, and design descriptions of their carrier spacecraft are included in the writeup. Detailed master equipment lists (MELs) for all flight system elements can be found in Appendix C.

Flagship Submersible

The Flagship submersible would be delivered by the Saturn orbiter to the Titan lake integrated with the floating element. The submersible would take a limited number of surface science measurements before descending to the bottom of the lake. During descent, the submersible would take compositional lake measurements at different depths while returning science data via VHF link through the lake medium to the floating element. Once on the bottom of the lake, the submersible would collect and analyze sediment samples. The submersible would remain at the bottom of the lake for 30 days, taking compositional samples and acquiring sonar data before returning to the surface and sending data to the Saturn orbiter on its second Titan flyby.

The submersible design consists of an instrument payload and four major subsystems—structure, power/command and data handling (C&DH), thermal, and telecom. Table 3-6 summarizes submersible subsystem mass and power. The structural design consists of two 0.7 m diameter metal spheres connected by a thin cylindrical tube containing the cabling from one sphere to the other. Science instruments and most of the batteries are housed in one sphere, while the telecom system, C&DH, and power electronics are housed in the other. When connected, the submersible mass outweighs the displaced fluid, causing it to sink to the lake bottom at a rate of approximately 1 m/s. At the end of 30 days, the sphere containing the instrumentation would be released, remaining at the lake bottom while the upper sphere would return to the surface to transmit data to the orbiter. Although the liquid medium is not fully known, the structural components have been designed with margin to ensure descent and resurfacing occurs given the widest expected range of possible lake densities.

The submersible power system would be comprised of lithium-carbon monoflouride (Li CFx) primary batteries. There would be no power generation located on the submersible. The Li CFx batteries are an energy-dense technology that have not yet been proven, but are expected to be developed prior to mission selection.

Table 3-6. Flagship Submersible Mass and Power

	Mass			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	106	30%	138	-	-	-
Thermal control	17	29%	22	4	43%	6
Propulsion (dry mass)	0	0%	0	-	-	-
Attitude control	0	0%	0	-	-	-
Command & data handling	3	30%	4	9	43%	13
Telecommunications	11	19%	17	70	43%	100
Power	26	30%	34	-	-	-
Total Flight Element Dry Bus Mass	**163**	**29%**	**215**	**N/A**	**N/A**	**N/A**

A new, small-format, modular approach would be used for the electronics allowing a combination of C&DH and electrical power system (EPS) functions in a single-integrated avionics assembly. An event timer module (ETM) would be designed for the submersible, providing the timing and control functionality while minimizing power. The main driver to move toward the ETM in place of a more traditional C&DH subsystem is to limit the power requirements and ultimately the drain on the primary battery. Instrument control and sequence event timing would be loaded into the ETM prior to separation from the floating lander. These modules would be developed specifically for the mission to meet the project needs. Figure 3-5 shows a block diagram of the ETM.

All versions of the Titan lake floating landers and submersibles would utilize the same thermal control approach, shown in Figure 3-6 to reject heat during cruise, while decoupling from the cold environment during and following EDL. Radioisotope heating units (RHUs) would be used for heat generation to keep the battery-powered submersible at operating temperature. The instruments would be thermally anchored together via a high-conductance structure. A heat strap would connect to a Starsys passive heat switch located on the inner surface of the outer shell. The heat switch would passively sense and maintain the temperature of the strap, and modulate the thermal connection to the shell wall. This segment of the shell wall would have sufficient thermal conductance to transport the rejected heat. The thermal strap would be insulated from the surroundings (vacuum during cruise, Titan atmosphere after EDL for ASRG-powered probes) so as not to be affected by convection. Convective heat transport would be suppressed by mechanical design and baffling if needed.

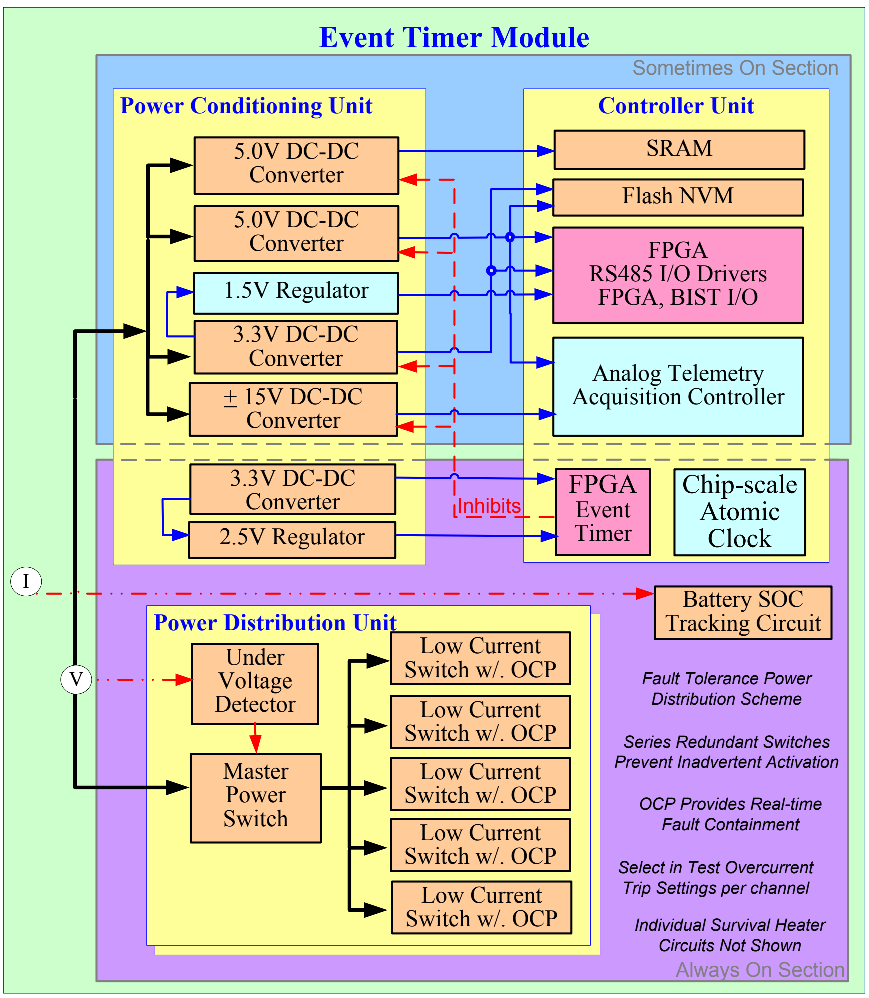


Figure 3-5. Event Timer Module Block Diagram

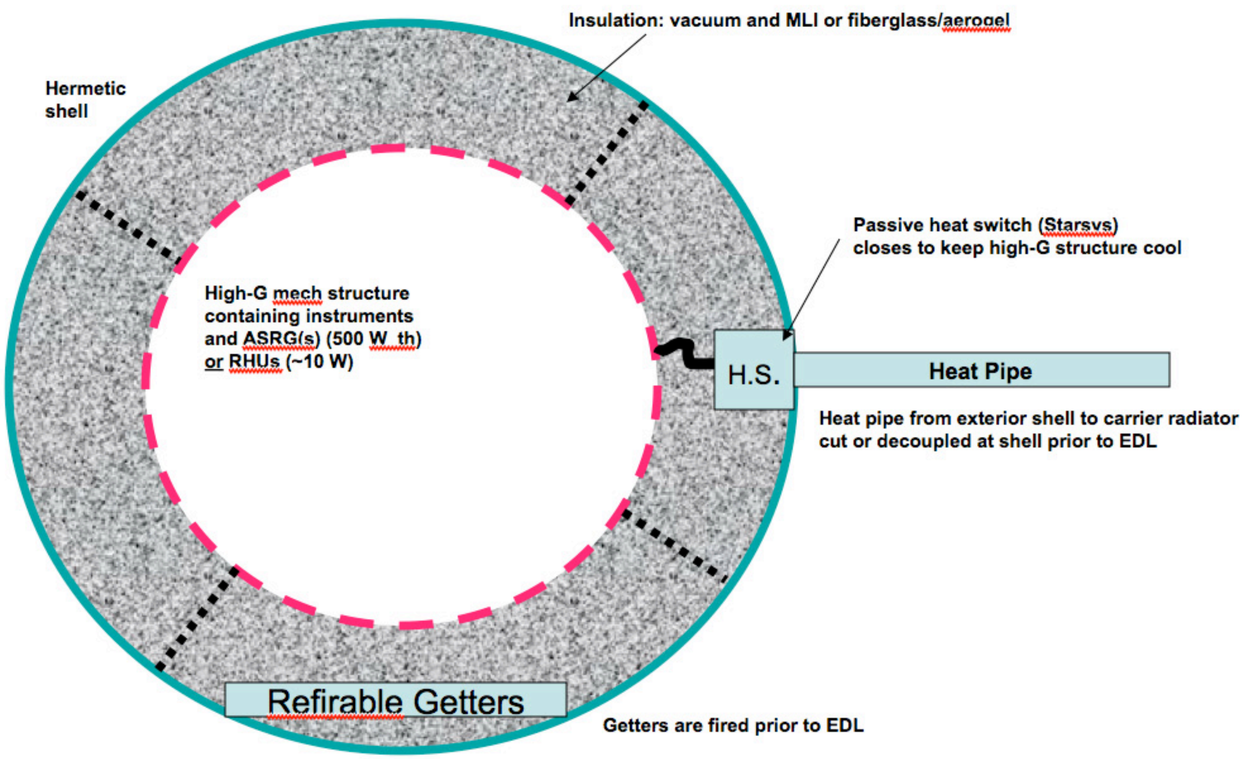


Figure 3-6. Thermal Design Concept

To maintain operational temperature of the instruments in the cryogenic Titan environment, the interiors of the probes would be insulated from the exterior shells. The submersibles would be hermetically sealed vessels, which would be maintained with vacuum inside and insulated by multilayer insulation (MLI). The vessels would be evacuated prior to launch, and all materials would be low-outgassing as far as practical. During cruise, vacuum would be maintained by refirable getters, which must be reactivated as vacuum degrades; this is done by passing an electric current through the getter body, which incorporates a resistive heater. The getters would be electrically accessible from outside the hermetic shell, so the reactivation can be done with external power, without interaction of the instrument. The last reactivation of the getter package would be done shortly before separation of the entry vehicle from the Saturn orbiter. Upon entry into the cold Titan atmosphere and lake, absorptive getters located on the inner surface of the hermetic shell would maintain vacuum inside the probe. Pressure in the probe must be below ~10^{-6} bar, in order for the MLI insulation to effectively maintain the instrument temperature; this is routinely achieved in cryogen storage vessels using similar absorptive getter materials.

The use of refirable getters adds to the operational complexity. An alternative approach to maintaining vacuum during cruise would be the use of a valve which would open after launch, allowing the probe interior to vent to space. The valve would close prior to EDL, and absorptive getters as above would maintain vacuum. The valve must reseal to a high degree and must maintain seal during the heating of EDL, the thermal shock of splashdown into cryogenic fluid, and the subsequent rise in pressure as the submersible descends. The risk of failure of the valve seal was felt to be unacceptable; it was also not clear that the mass of the valve would be less than that of the getter package (this will depend on design details of the probe). Therefore, the choice was to use the refirable getter package.

The submersible would utilize two methods of relaying data taken from the lake depths—through the medium to the floating element as well as directly to an orbiting spacecraft upon resurfacing. For through-the-medium communication during the initial descent, a transmit-only VHF system would use a 1 m deployable crossed dipole antenna attached to the exterior of the submersible to transmit to the floating element. This information can be stored onboard the floating element to be sent back to the orbiter if an anomaly occurs and the submersible is unable to resurface. Due to the uncertainty regarding currents

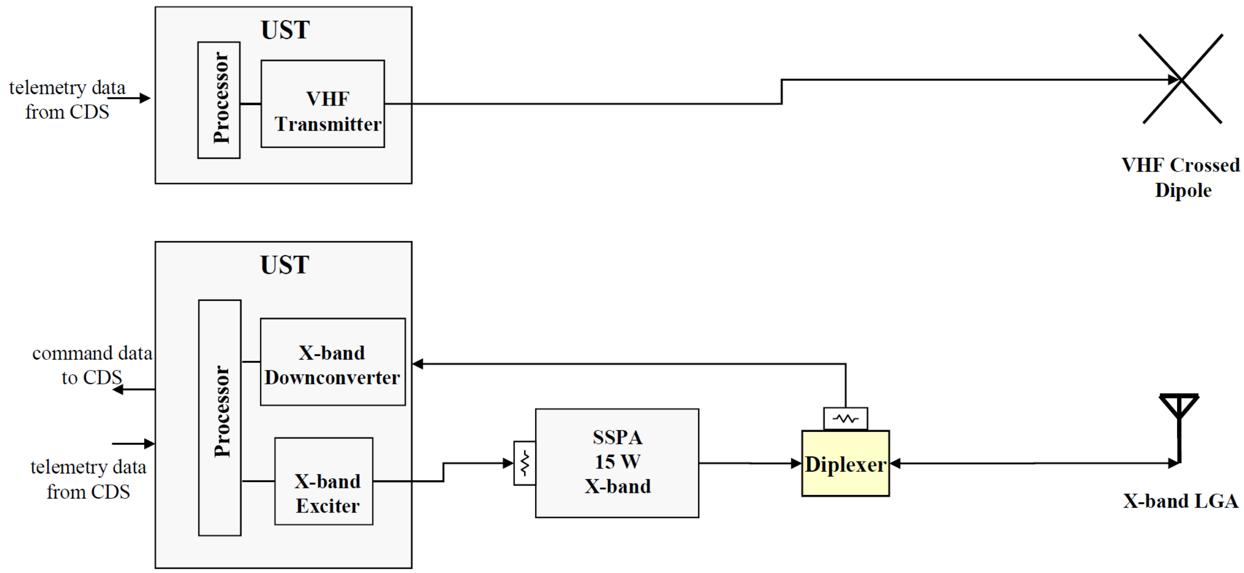


Figure 3-7. Flagship Submersible Telecom Block Diagram

and surface winds, the line of communication between the two elements may not be reliable for long after submersible descent. Therefore, primary data return would be provided by a X-band system using a single zenith-pointed low-gain antenna (LGA), allowing communication directly to the Saturn orbiter upon resurfacing. Two independent Universal Space Transponder (UST) would serve as the radios for both the VHF and the X-band systems providing functional redundancy for the telecom system. The UST is a software-defined radio currently under development at JPL as the next-generation deep space transponder. With heritage from the Electra relay radio, the UST has a reprogrammable baseband processor, which is link-frequency independent, as well as frequency-dependent circuit slices, which support the RF-processing functions. More than one set of circuit slices can be connected to the baseband processor, thus enabling simultaneous operation in more than one frequency band. Current UST development plans include an X-band RF slice, but VHF RF slices would most likely need to be developed for the submersible-to-floating lander relay link. Although both technologies have been proven in the space environment, communication through a liquid ethane medium has not been proven and will require some development and testing to be done by the project. Figure 3-7 shows a block diagram for the submersible's telecom system.

Flagship Floating Lander

The floating lander would enter the Titan atmosphere packaged with the submersible inside a 2.6 m aeroshell before parachuting to the lake surface. Once on the lake surface, the floating lander would perform science measurements of surface properties and lake-atmospheric interactions as well as provide release of and communication with the submersible during lake descent.

The floating lander structure has been designed to accommodate the submersible, carrying it to the surface and distributing the loads of lake impact. In order to do so, the lander is designed to enter the lake stern-first, in an attempt to minimize the surface area that will impact the lake surface, much like a diver entering the pool after a dive. This method of descent reduces the added structure required to absorb the impact of landing. Figure 3-8 shows configurations for both the submersible and floating lander. Table 3-7 provides the MEL for the lander.

The power system of the floating lander would utilize two ASRGs for power generation. During launch and cruise, the power would be shunted and the heat would be rejected by external radiators to prevent overheating. In addition to ASRG power generation, the power system would include multiple advanced Li-Ion primary batteries to meet the temporary additional loads required for telecom and science operations.

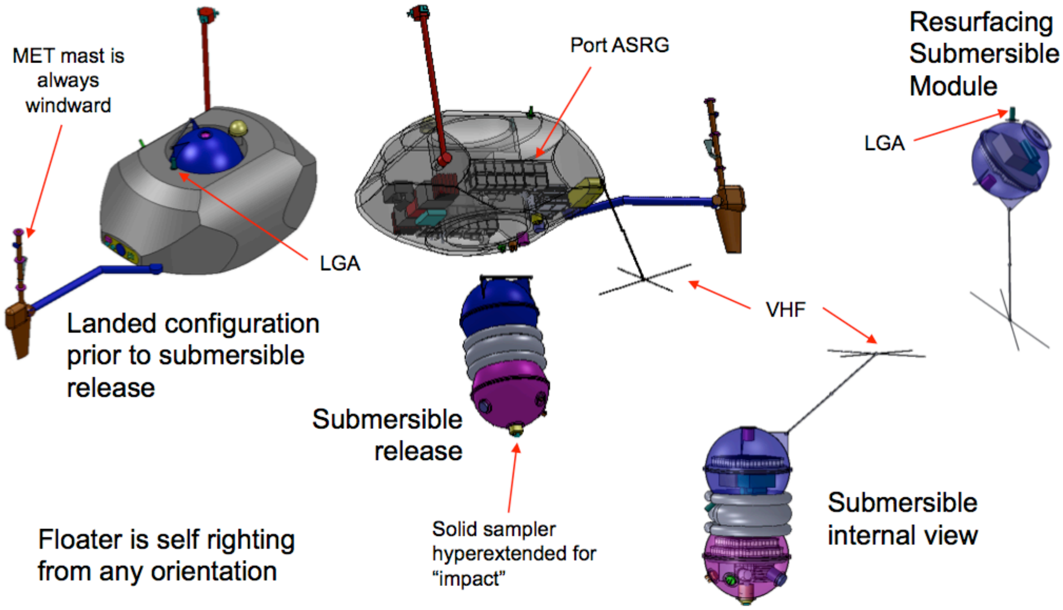


Figure 3-8. Flagship Floating Lander and Submersible Configurations

The floating lander is required to control all in-situ elements of the Flagship option. The floating lander's C&DH subsystem design is based on JPL's MSAP architecture, as shown in Figure 3-9. The lander's avionics, depicted in the lower left of the integrated block diagram, are fully adequate to interface with the large number of science instruments required for the Flagship mission. The MSIAs and MCIC boards would provide instrument interfaces while the MTIF would provide the interface to the telecom radio. The computer and memory would provide sequencing under flight software control and additional storage for science data. The critical relay controller board would provide hardware protection for critical functions (e.g., protection against inadvertent pyrotechnic events and computer boot code bank selection).

The floating lander would utilize a redundant, two-way X-band system for communication to the orbiting spacecraft and a redundant, receive-only VHF system for submersible communication. The floating lander telecommunication subsystem is very similar to the submersible, using the same types of antennas as well as the UST as the radio for both telecom bands. Figure 3-10 shows the telecom block diagram.

The floating lander would utilize a similar design for thermal control as the submersible with the exception of heat generation. Waste heat from the ASRGs would be distributed throughout the lander, eliminating the need for RHUs. A major difference is that the floating lander would not be a hermetically sealed volume; it would be vented in a controlled fashion during descent to allow pressure equilibration with the surrounding atmosphere, which is mostly N_2. The floating lander would be insulated with a layer of aerogel on the inner surface of the shell, which would provide sufficient insulation to maintain inner temperature.

Science requires knowledge of wind direction, which in turn requires knowledge of the floating lander heading angle. The Flagship mission would operate during Titan night at the target lake, where sun sensors are not an option. Instead, a Saturn camera would be developed for this mission. Its heritage HgCdTe detector would be sensitive in the 2 to 5 micron range. Titan's atmosphere has windows at both ends of that range.

In order to mitigate any atmospheric disturbances that may occur due to the floating lander, booms containing the atmospheric instrumentation would be mounted in such a way as to always be up wind of the floating lander. This is achieved by placing a small keel at one end of the lander to act as a pivot point orienting the bulk of the lander downwind.

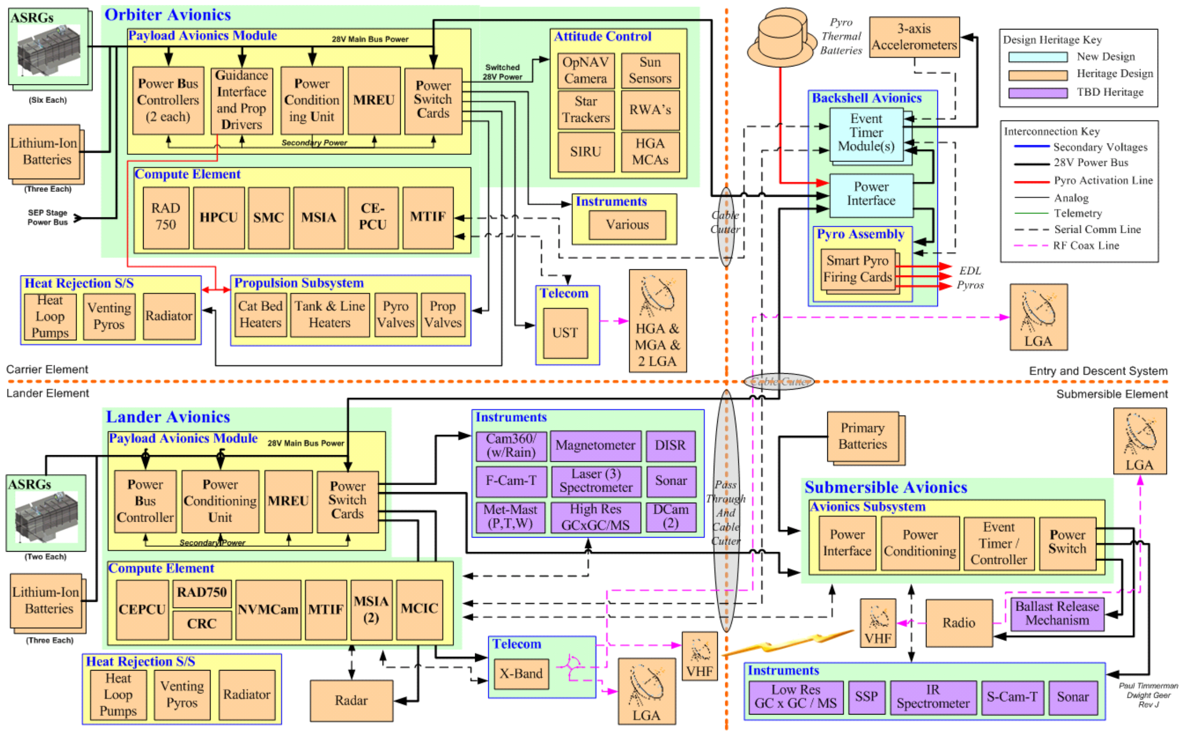


Figure 3-9. Flagship System Block Diagram

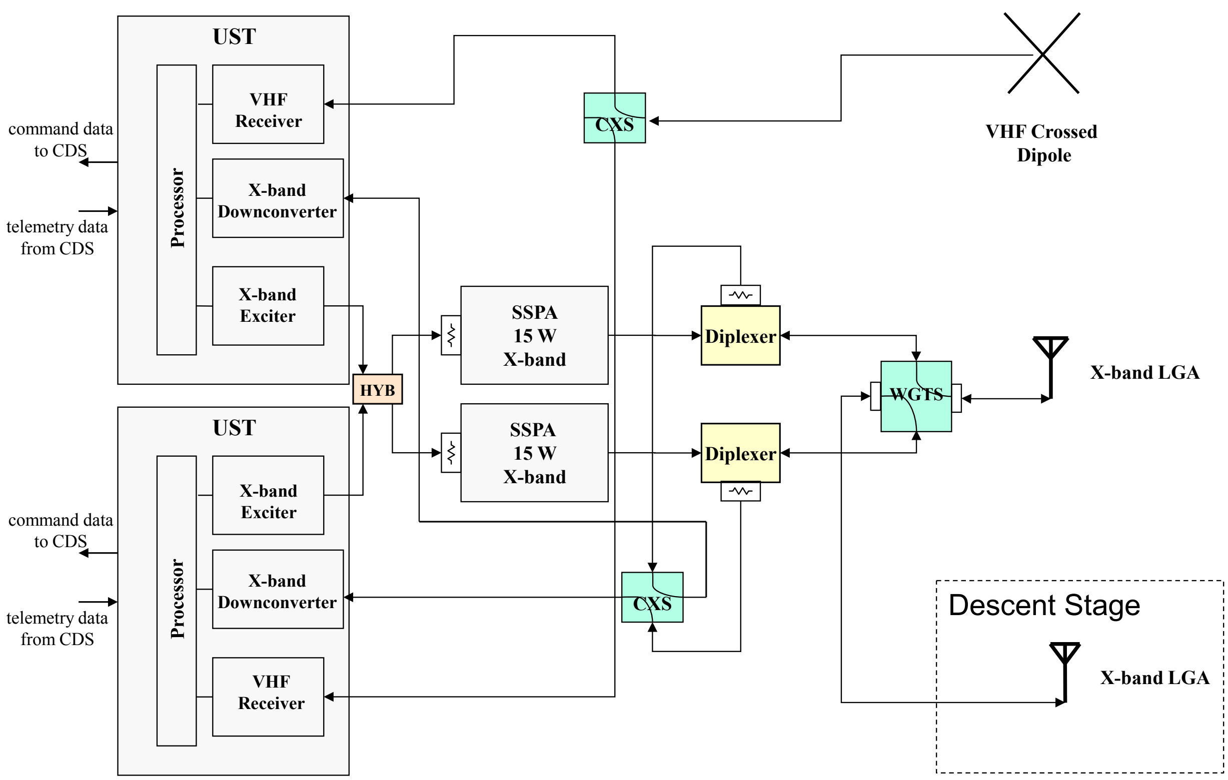


Figure 3-10. Flagship Floating Lander Telecom Block Diagram

Table 3-7. Flagship Floating Lander Mass and Power

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	157	30%	205	-	-	-
Thermal control	28	30%	36	10	43%	14
Propulsion (dry mass)	0	0%	0	-	-	-
Attitude control	14	23%	18	7	43%	9
Command & data handling	25	7%	27	45	43%	64
Telecommunications	17	19%	20	65	43%	68
Power	81	30%	105	-	-	-
Total Flight Element Dry Bus Mass	**322**	**28%**	**411**	**N/A**	**N/A**	**N/A**

New Frontiers Direct-to-Earth Floating Lander

The DTE New Frontiers–class mission was developed to determine the feasibility of DTE communication from the Titan surface. In order to communicate with Earth, the mission must be flown during daylight at the target lake, significantly constraining the timeline of the mission as well as adding new requirements for the flight system.

Much like the Flagship mission, the New Frontiers DTE lander would be delivered to the surface by parachute in such a way that would minimize the surface area impact when entering the lake. However, unlike the Flagship lander, the structure of the floating lander must house a 0.8 m HGA required for communication with Earth. This antenna would be housed within a RF-transparent shell and would be used throughout surface operations.

The RF-transparent radome containing the relay antenna would utilize thermal insulation in the inner surface of the shell. The interior of the shell would contain Titan atmosphere, mostly N_2, at ~290 K and ~1.6 bar. The insulation would be designed to retain sufficient heat to maintain the instruments and avionics at operational temperature, with the 1 KW (thermal) waste heat from the ASRGs being the heat source, and the outer surface at ~94 K. Silica aerogel, a highly non-conductive dielectric, proposed as the insulation material. A 25 mm thick layer of aerogel on the inner surface would maintain the interior volume at 290 K while attenuating an X-band signal by <3%. Figure 3-11 depicts the configurations for the New Frontiers DTE lander and Table 3-8 provides the flight system MEL.

The New Frontiers DTE floating lander would have a redundant, two-way X-band system. Like the Flagship lander, the system would use USTs as the telecom subsystem’s radio; however, only an X-band RF slice would be used since there would be no Ka-band communication. Two 35 W RF travelling wave tube amplifiers (TWTAs) would power the downlink. An X-band LGA would allow EDL carrier tracking by a radio telescope, but for data return, a gimbaled 0.8 m X-band HGA would be used. Due to the rocking motion of the moving liquid, a gimbaled system similar to that used on terrestrial ocean-going ships would orient the antenna, maintaining lock on Earth with the help of a DSN uplink beacon. The telecom system block diagram and link analysis for the New Frontiers DTE mission can be found in Figure 3-12 and Table 3-9, respectively.

The floating lander’s inertial orientation would be used to determine where to point the HGA for DTE communications. An uplink beacon sensed by the HGA would be used for auto-tracking after acquisition. An alternate strategy to save mass, power, and cost would be to search open-loop for the uplink beacon with no onboard determination of inertial orientation. Uncertainty regarding how much the floating lander would rock or change heading due to wind and waves led to a strategy using onboard attitude determination.

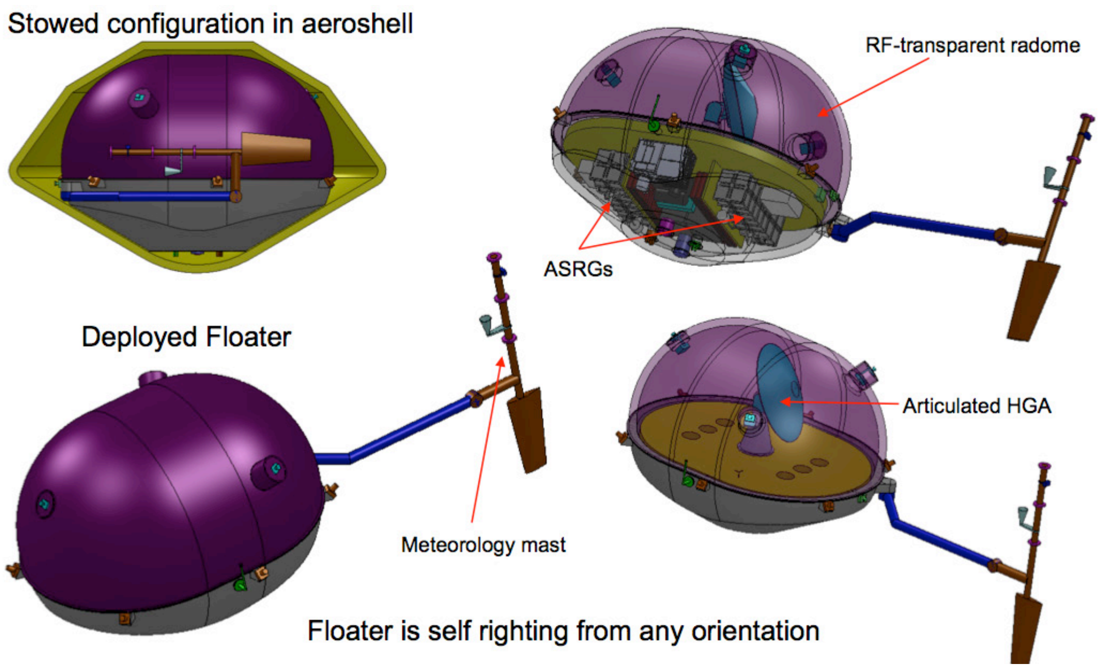


Figure 3-11. New Frontiers DTE Floating Lander Configuration

Table 3-8. New Frontiers DTE Floating Lander Mass and Power

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	152	30%	198	–	–	–
Thermal control	18	29%	23	4	43%	6
Propulsion (dry mass)	0	0%	0	–	–	–
Attitude control	4	15%	5	16	43%	23
Command & data handling	26	8%	28	49	43%	70
Telecommunications	22	14%	25	76	43%	109
Power	98	30%	127	–	–	–
Total Flight Element Dry Bus Mass	**320**	**27%**	**406**	**N/A**	**N/A**	**N/A**

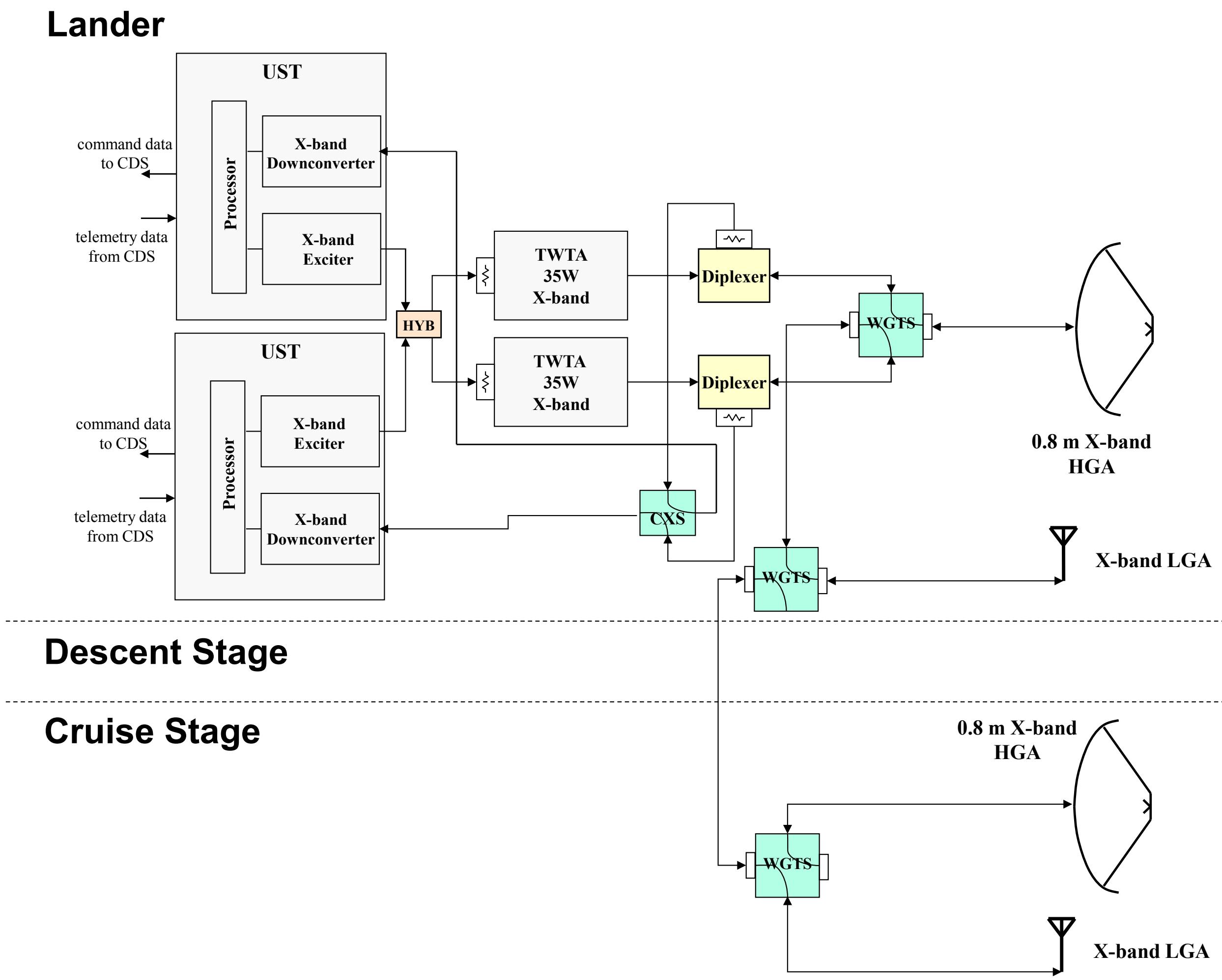


Figure 3-12. New Frontiers DTE Telecom Block Diagram

Table 3-9. New Frontier DTE Telecom Link Analysis

Link Description	LGA Safe Mode Downlink	HGA Downlink (Cruise/Surface)	HGA Uplink (Cruise/Surface)
Data Rate	10 bps	440 bps	1000 bps
TRX Antenna	LGA, 20^{o} off point	HGA, 1^{o} off point	34 m BWG
TRX Power (RF)	35 W	35 W	20 kW
Range	2.8 AU	11 AU	11 AU
RCV Antenna	70 m	34 m BWG	HGA, 1^{o} off point
Coding	Turbo 1/2, 1784 bit frame	Turbo 1/6, 8920 bit frame	Uncoded
Margin	3.0 dB	3.0 dB	3.7 dB

While the floating lander is on the lake surface, gyros, accelerometers, and sun sensors would be used to sense orientation, and the floating lander would be passively stable (e.g., rocking slowly). A redundant set of IMUs and six JPL advanced-integrated micro-sun sensors (AIMS) would be used for redundant hemispherical coverage. Accounting for atmospheric absorption, solar intensity on the surface appears to be comparable to solar intensity in space at 30 AU. JPL AIMS sun sensors are qualified for up to 30 AU. With the sun direction, nadir direction (from accelerometer measurements), and accurate ephemeris information, the inertial orientation of the floating lander can be determined. Gyros would be used to propagate orientation while the floating lander rocks or changes heading in between sun and nadir vector measurements.

The floating lander would utilize two ASRGs for power generation. Power control would be accomplished through a shunt regulator / shunt radiator system. The power conditioning included in the EPS mass estimate would be limited to the internal needs of the power chassis only. It is assumed that all separation events after EDL would be accomplished using non-explosive actuator mechanisms, and thus a dedicated pyro-firing assembly would not be included in the lander. Power switching would be provided for the lander subsystems, including C&DH, telecom, thermal control, mechanisms, and instruments. These are MSAP-based electronics, including a board-based power analog module (PAM) and a slice-based power assembly (PA), as was used on MSL.

The lander would also contain a similar MSAP avionics design as the Flagship floating lander. Consisting of a RAD750 for processing and multiple interface boards, the avionics architecture would be capable of handling the science operations and DTE communication required for the mission. Figure 3-13 shows the avionics block diagram.

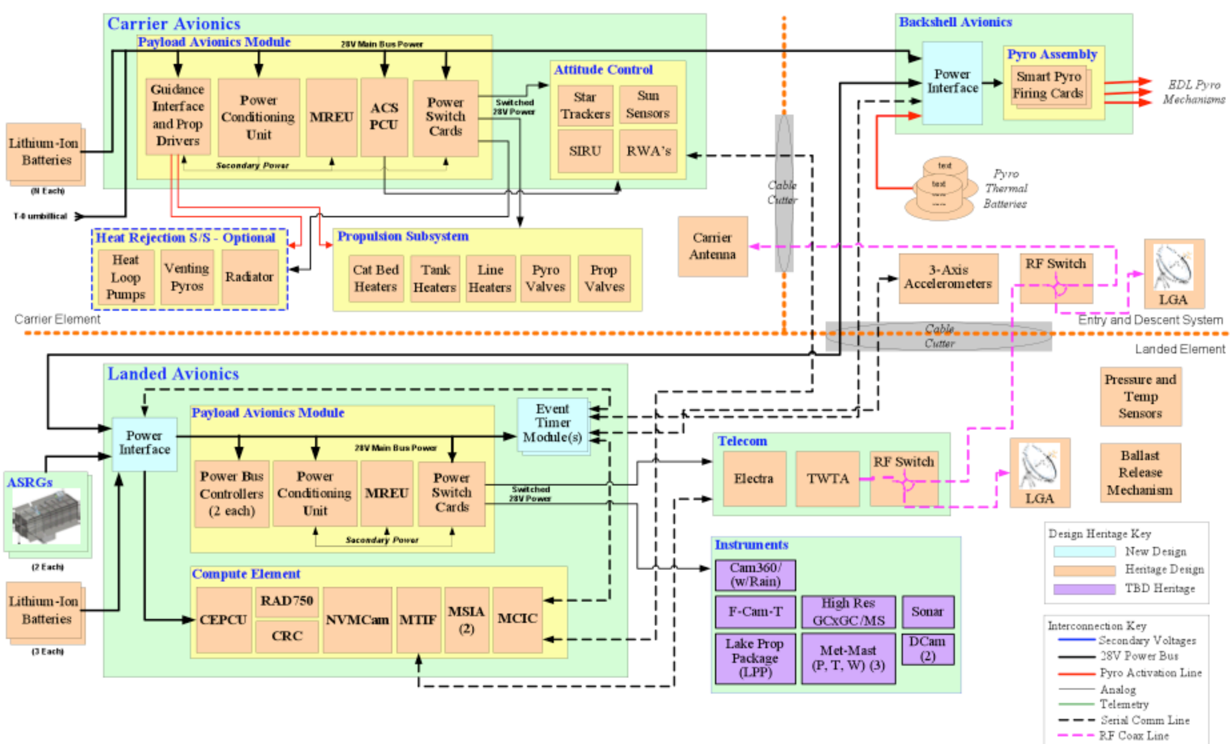


Figure 3-13. New Frontier DTE System Block Diagram

New Frontiers Relay Submersible

The New Frontiers relay submersible is a low-cost design that would allow for sample acquisition at the lake surface, bottom, and depths in between. The submersible would be delivered to the Titan surface packaged in a 2.1 m aeroshell where it would take samples at the lake surface before submerging to the bottom of the lake.

The operational scenario puts some constraints on the structural design, requiring the submersible to float before submerging. This constraint was not necessary in the Flagship mission, where the floating lander would keep the submersible afloat prior to release. In order to address this constraint, small-evacuated floats would be attached to the submersible in such an orientation as to keep the lander upright during surface operations. Once the surface operations have commenced, the floats would be opened, filling with liquid to decrease buoyancy of the vehicle and allow it to sink.

As shown in Figure 3-14, the primary structural design consists of two 0.7 m diameter metal spheres connected by a thin cylindrical tube containing the cabling from one sphere to the other. As with the Flagship submersible, science instruments and most of the batteries would be housed in one sphere, while the telecom system and necessary electronics would be housed in the other. When connected after the floats are flooded, the submersible mass would outweigh the displaced fluid, causing it to sink. At the end of the submerged science operations, the sphere containing the instrumentation would be released, remaining at the lake bottom while the upper sphere would return to the surface to transmit data to the cruise/relay stage during its flyby. Although the liquid medium is not fully known, the structural components have been designed with margin to ensure descent and resurfacing occurs given the widest expected range of possible lake densities. The project would be responsible for ensuring the mechanical integrity and testing of the submersible in a similar environment. Table 3-10 provides the submersible MEL.

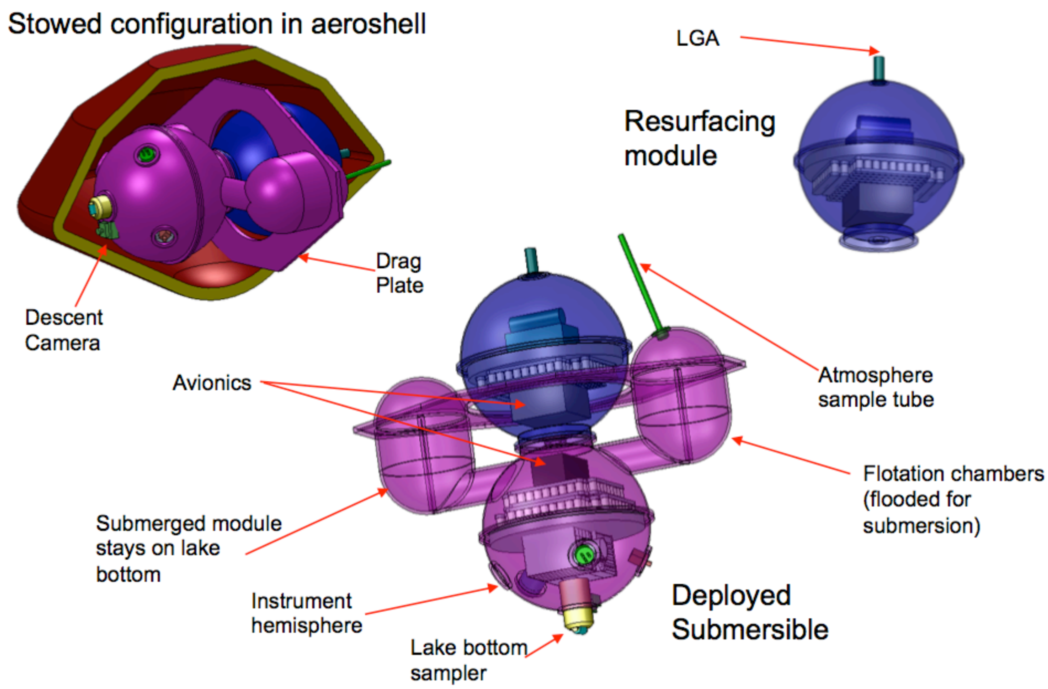


Figure 3-14. Relay Submersible Configuration

Table 3-10. New Frontiers Relay Submersible Mass and Power

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	124	30%	161	-	-	-
Thermal control	20	29%	27	4	43%	6
Propulsion (dry mass)	0	0%	0	-	-	-
Attitude control	0	0%	0	-	-	-
Command & data handling	3	30%	4	9	43%	13
Telecommunications	16	0%	16	75	43%	107
Power	32	30%	41	-	-	-
Total Flight Element Dry Bus Mass	**195**	**27%**	**249**	**N/A**	**N/A**	**N/A**

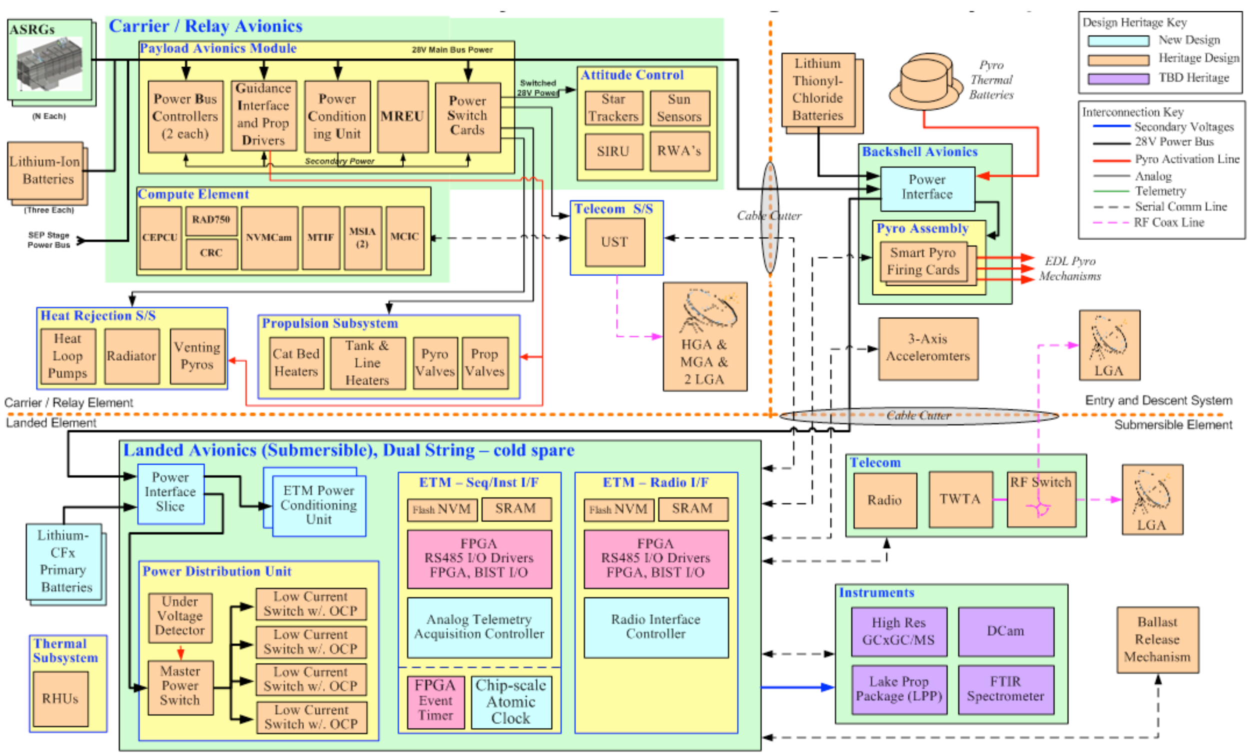


Figure 3-15. New Frontiers Relay Submersible System Block Diagram

The submersible power source would be comprised of Li CFx primary batteries. There would be no power generation located on the submersible. The Li CFx batteries are an energy dense technology that have not yet been proven, but are expected to be developed prior to mission selection. A new, small-format, modular approach is used for the power electronics, allowing a combination of C&DH and EPS functions in a single-integrated avionics assembly. The same ETMs described in the Flagship submersible design would be employed for the New Frontiers submersible. Two ETMs would be designed specifically for the mission, providing the necessary functionality and memory in a smaller, more functional design. Figure 3-15 shows the submersible block diagram.

The New Frontiers submersible would utilize the same thermal design as the Flagship submersible. The hermetically sealed submersible would use vacuum getters to maintain vacuum while RHUs would provide the necessary heat to keep the instruments and avionics at operating temperature. High-

conductance structure, heat straps, and switches would be used to moderate the thermal connections to the shell wall.

The submersible would use a redundant X-band system with X-band-only USTs and 15 W solid-state power amplifiers (SSPAs). The system would use a single X-band LGA for communications. The submersible would carry out science operations while the cruise/relay stage approaches Titan. After six hours at the bottom of the lake, the submersible would return to the surface and relay all data to the cruise stage during the four hours of closest approach. The relay link would be full duplex and would use Proximity-1 standards as well as ADR. The cruise/relay spacecraft would return all the data to Earth over the following week.

New Frontiers Relay Floating Lander

The New Frontiers relay floating lander was designed to be the lowest-cost Titan Lake Probe mission that would be above the science floor for this study. The design of the lander leverages the design produced for the New Frontiers relay submersible with a shorter mission timeline and a descoped set of science instruments. The lander would be delivered to Titan using the same entry system as the submersible.

The floating lander is designed with simplicity in mind. Figure 3-16 shows the configuration of the lander. Shaped like a barrel, the masses of the subsystems are distributed in such a way as to be self-righting when immersed in the liquid. The masses of the instrumentation and batteries would be located on the same side of the barrel in order to cause that side always to be oriented down. This design has the added benefit of dampening any motion that may be caused by surface chop in the liquid, ensuring a stable platform for telemetry and science operations. Table 3-11 provides the MEL for the New Frontiers relay floating lander.

Thermal control for the lander would be very similar to the battery-powered submersibles. As with the submersibles, the floating lander would be a hermetically sealed vessel, maintained with internal vacuum and insulated by MLI. Vacuum would be maintained by refirable getters and heating would be provided by RHUs.

Lithium-carbon monoflouride primary batteries would power the lander. These energy-dense primary batteries must support the energy required for the duration of the landed mission, supporting all instrument operations and subsystem power requirements. The lander power electronics suite would include power distribution and regulation as well as ETM functions. No power control is required for a primary battery powered system, as discharge voltage alone suffices. Power switching would be provided for the lander subsystems, including C&DH, telecom, thermal control, mechanisms, and instruments.

The lander’s avionics suite would consist of two ETMs to handle spacecraft operations. ETMs would require much less power by integrating minimal functionality into single module. At times of minimal operations, the ETM can basically turn off everything except for a timer that would send a signal to wake up the spacecraft. This operational method would significantly reduce the power draw from the electronics, reducing battery size and mass. Figure 3-17 shows the spacecraft avionics system.

The floating lander would utilize the same communication strategy as the New Frontiers submersible. Communication to the relay spacecraft may be possible at a very low rate beginning at entry, and would extend until the relay spacecraft goes over the horizon approximately 12 hours later. A redundant X-band system, depicted in Figure 3-18, with X-band-only USTs and 15 W SSPAs transmitting through a zenith pointed LGA would relay science data to the flyby spacecraft.

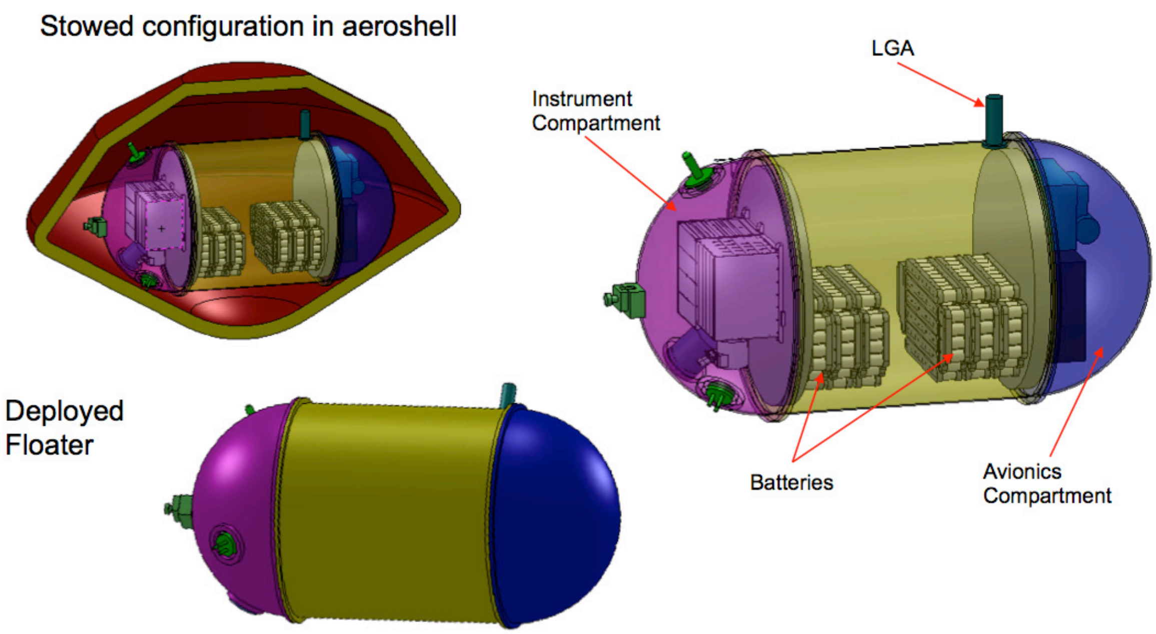


Figure 3-16. New Frontiers Relay Floating Lander Configuration

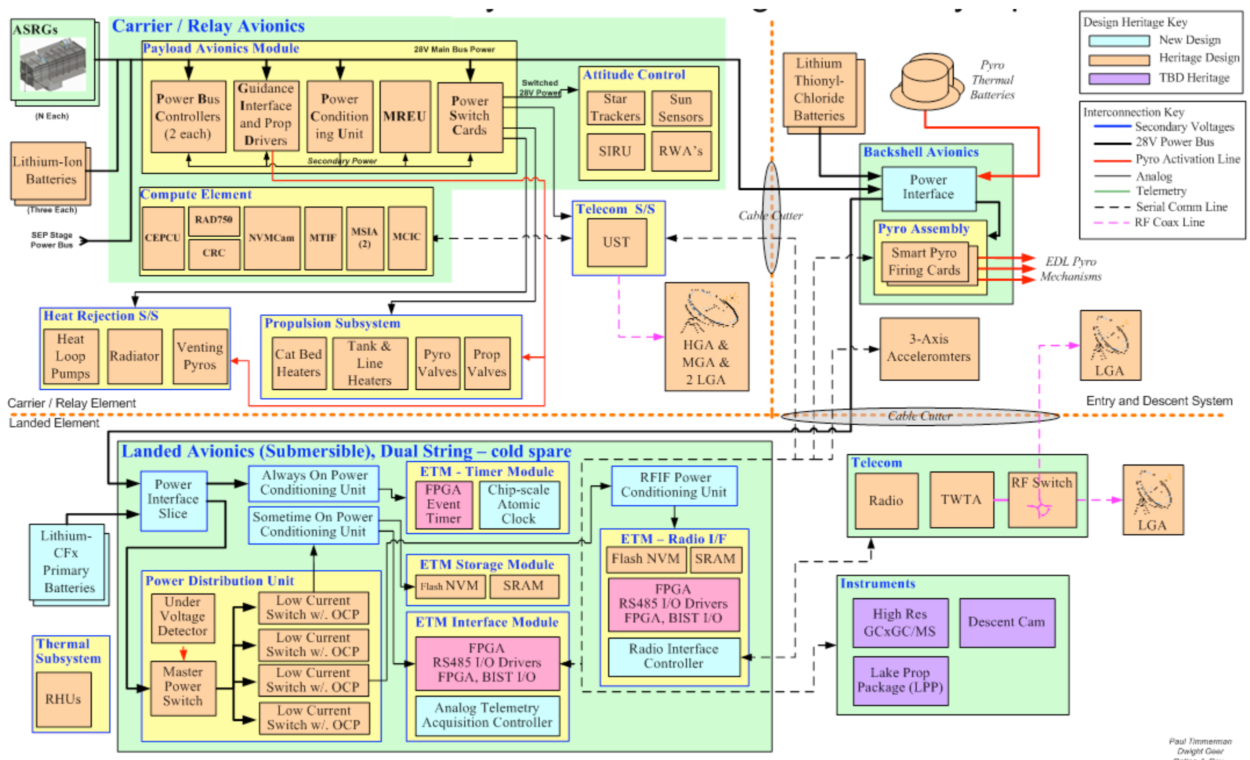


Figure 3-17. New Frontiers Relay Floating Lander System Block Diagram

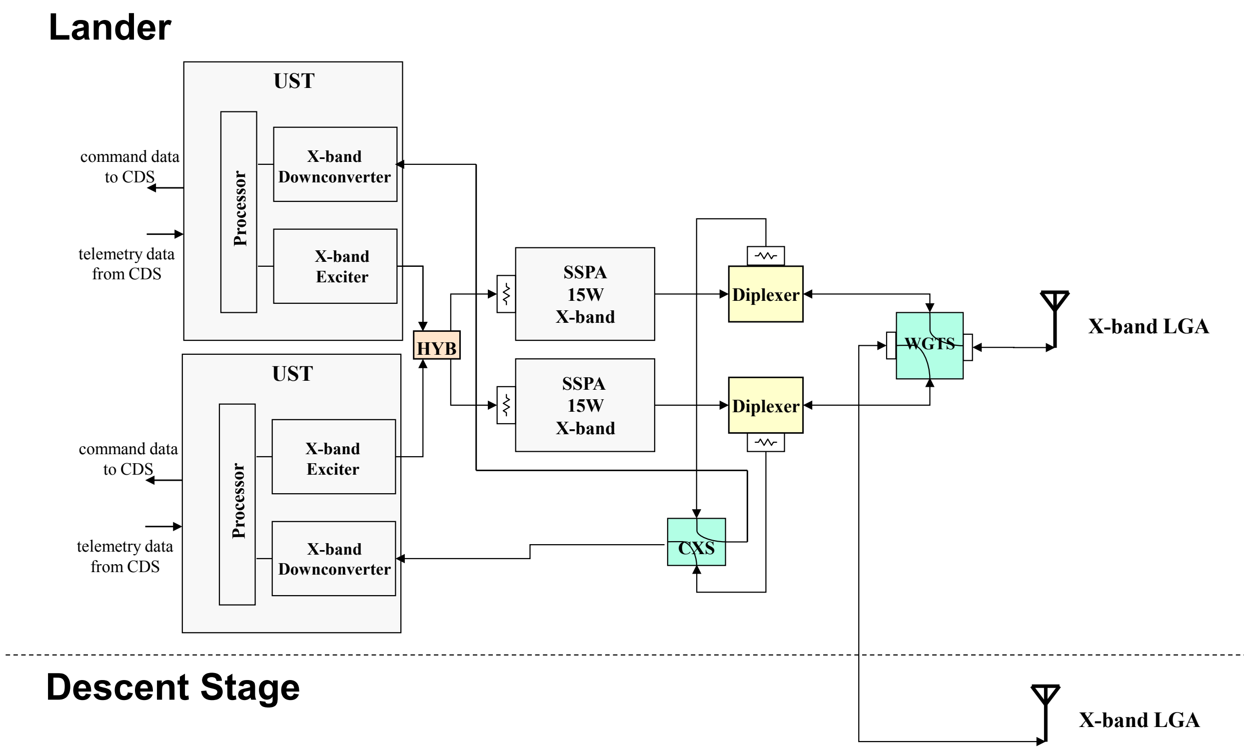


Figure 3-18. New Frontiers Relay Lander Telecom Block Diagram

Table 3-11. New Frontiers Relay Floating Lander Mass and Power

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	72	43%	94	-	-	-
Thermal control	21	43%	27	4	43%	6
Propulsion (dry mass)	0	0%	0	-	-	-
Attitude control	0	0%	0	-	-	-
Command & data handling	3	30%	4	9	43%	13
Telecommunications	16	0%	16	75	43%	107
Power	26	30%	34	-	-	-
Total Flight Element Dry Bus Mass	**138**	**43%**	**175**	**N/A**	**N/A**	**N/A**

Table 3-12. Titan Lake Lander Entry Systems

	Flagship	New Frontiers DTE	New Frontiers Relay Submersible	New Frontiers Relay Floating Lander
Aeroshell diameter (m)	2.6	3	2.1	2.1
Aeroshell mass (kg)	330	203	176	109
Entry system mass (kg)	556	355	324	218

Entry Systems

The Titan lake entry system would be comprised of all the equipment necessary to allow the landers to land safely on the surface of Titan after release from the carrier/orbiter spacecrafts. The driving requirements for this particular design are the total landed mass / volume and atmospheric conditions upon entry. Parametric modeling based on actuals was used to estimate the mass of the structural portion of the aeroshell, while the spacecraft sizing determined the necessary volume. Analysis of the Titan atmosphere has determined that a 60-degree aeroshell is necessary for this environment, deviating from the 70-degree aeroshells used for Mars. The design of the aeroshell would leverage Huygens heritage wherever possible. Table 3-12 provides a breakdown of aeroshell diameters and masses for the different types of missions.

Although the entry system would be largely composed of structure, several other functionally simple subsystems would also be required to successfully execute the EDL phase of the mission. A single LGA would be located on the backshell for the Flagship and relay missions allowing for communication during descent. For the DTE mission, communication would be lost between cruise stage release and backshell separation. Once separated, tone communication would occur through an LGA on the lander to provide Doppler tracking. In all cases, the antennas would use lander radios and avionics for communication.

The entry system would contain no control avionics, however, it would have dedicated pyro-thermal batteries for lander separation, as well as primary batteries to support detached cruise mode. These are conventionally Li-SO_2 or Li-$ASOCl_2$ batteries, but could just as easily be Li-CF_x instead.

Accelerometers would be used to measure the deceleration profile during entry, and MER heritage algorithms would be used to determine when to deploy the parachute. The location of the accelerometers varies based on the type of mission. In the case of the Flagship mission, the accelerometers would be located on the lander, but would provide the same functionality as they would on the entry system. All New Frontiers missions would have the accelerometers mounted to the backshell.

Thermal insulation thickness varies for ASRG- and RHU-heated entry systems. For the Flagship and DTE landers, the ASRGs would be housed within the aeroshell forcing heat to be rejected. The relay landers would have ASRGs on the relay stage and rely on RHUs for heating. During cruise, a thermal strap would connect the warm components to a passive heat switch located at the inner surface of the shell; the switch would passively regulate the temperature of the interior. The exterior side of the shell would be connected via heat pipe to a radiator on the aeroshell allowing for heat rejection when needed.

Carrier Stage DTE

The New Frontiers DTE mission would use a “dumb” cruise stage to deliver the lander to Titan as illustrated in Figure 3-19. Using the avionics and power from the lander, the cruise stage would effectively be a large propulsion system. Due to the high delta-V requirement to get to Titan while Earth is in view, a large dual-mode bipropellant propulsion system would be necessary. Bipropellants are much more fuel efficient; however, they come with an added degree of complexity, as two types of propellant are necessary. One 110 lbf Hi-PAT bipropellant thruster would be used for large propulsive maneuvers while twelve 0.2 lbf monopropellant thrusters would utilize the propulsion systems fuel to provide attitude control and small delta-V maneuvers. The fuel and oxidizer used for this system would be hydrazine and nitrogen tetroxide. This type of a system is very efficient since it employees the benefits of bipropellant systems for large maneuvers and monopropellant systems for small maneuvers.

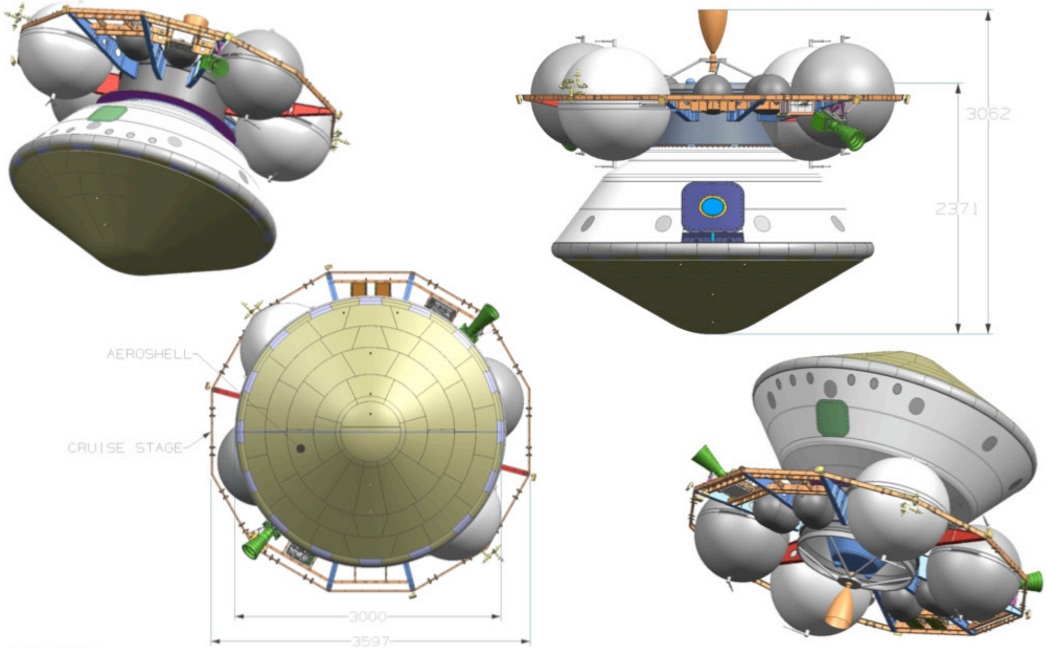


Figure 3-19. New Frontiers DTE Cruise Stage and Aeroshell

Attitude control would use star trackers, gyros (within an IMU), and sun sensors for sensing orientation; thrusters and a gimbaled main engine would be used to provide control torque for 3-axis stabilization. During long intervals of quiescent cruise, one of the star trackers would be used for all stellar attitude determination, and the IMU would remain off to conserve gyro life. For delta-V maneuvers and probe deployment, a star tracker and gyros would be used for stellar inertial attitude determination. Gyros and sun sensors would be used during launch and for a sun-safe mode.

The telecom equipment on the cruise stage would consist only of an X-band LGA and 0.8 m HGA, which would be connected to the lander’s telecom system by separable waveguide. The LGA would be used for early cruise communications and safe-mode communications out to 2.8 AU. The HGA would be identical to that on the floating lander but body-fixed, and would be used for all communications in the latter portion of cruise**.**

The lander’s ASRGs would provide power generation for the cruise stage during the life of the mission. For events that exceed the power provided by the ASRGs, such as DSMs, advanced Li-Ion secondary batteries would be used. The C&DH and EPS electronics would utilize MSAP technology with minimal functionality. Propulsion drivers and power conditioning units would be mounted aboard the cruise stage to run the propulsion system. All other control would be handled by the avionics aboard the landed element.

Relay Cruise Stage

The New Frontiers relay carrier stage would deliver either the floating lander or submersible to Titan as depicted in Figure 3-20. Unlike the “dumb” cruise stage used for the DTE floating lander, however, this stage must perform all the functions of a free-flying spacecraft and thus would include all the necessary avionics both to control itself and to act as a communication relay for the in-situ vehicle. The longer cruise times associated with these missions would bring the benefit of a reduction in the amount of delta V required relative to the DTE New Frontiers mission, allowing for a cheaper blowdown monopropellant system to be used. Although not as efficient as the bipropellant, the monopropellant system would significantly reduce the complexity of the system. The propulsion subsystem would be comprised of four 50 lbf thrusters used in unison for deep-space maneuvers (DSMs). All engines would be fired simultaneously to reduce the duration of the maneuver. Twelve 0.2 lbf thrusters would be used in pairs for attitude control maneuvers. The fuel used for this system would be hydrazine.

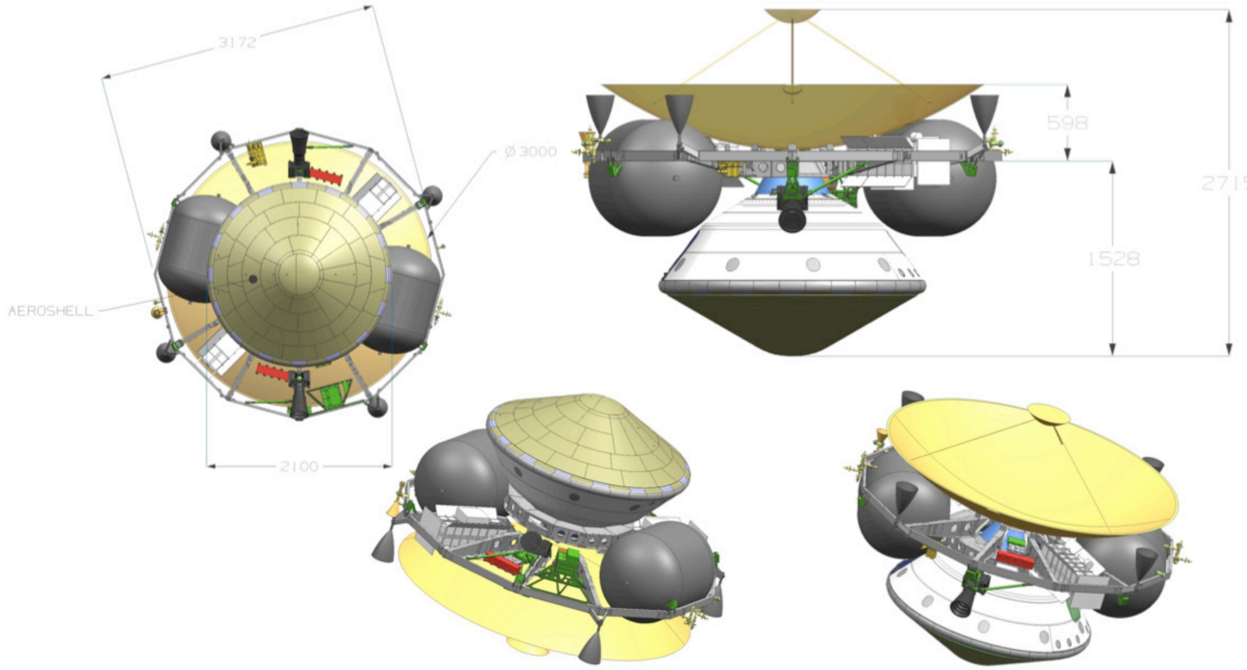


Figure 3-20. New Frontiers Relay Cruise Stage and Aeroshell

The relay cruise stage would employee the same attitude determination, control methodology, and thermal design as the DTE cruise stage. Star trackers, gyros (incorporated in the IMU), and sun sensors would be used for sensing orientation while thrusters would be used to provide control torque for 3-axis stabilization. Propellant heaters, heat pipes, and MLI would be used to keep the relay stage at operating temperature throughout the life of the mission.

An X-band relay system, depicted in Figure 3-21, would allow periodic checkouts of the lander/entry system during its detached cruise and would be able to receive semaphore tones from the lander during EDL. The lander would carry out science operations while the cruise stage approaches Titan and would then relay all data to the cruise stage at X-band during the four hours of closest approach. The cruise stage would have a redundant X- and Ka-band system. Two USTs would transmit and receive at X-band for either relay or DTE communication and would transmit only at Ka-band for DTE communication. Amplifiers would include 15 W RF X-band SSPAs and 25 W RF Ka-band TWTAs. A 3 m X- and Ka-band HGA would be used for relay and high-rate DTE communication, an MGA would be used for safe mode out to 7 AU, and two LGAs would provide early cruise communications. Table 3-13 provides the cruise stage link analysis.

The power system for the relay cruise stage would be similar to the DTE version with the exception of the location of the ASRGs. These power generation units would be housed aboard the cruise stage itself rather than on the landers. This architecture would force the landers to be completely battery-powered; however, would significantly reduce the cabling required to transport power.

The cruise stage avionics suite would be based on an MSAP architecture in which all the necessary interfaces and boards are integrated together. A RAD750 processor would act as the spacecraft's onboard computer; its associated nonvolatile memory would house the data received from the landed elements prior to downlink. Block diagrams for the relay/cruise stage can be found in Figures 3-15 and 3-16.

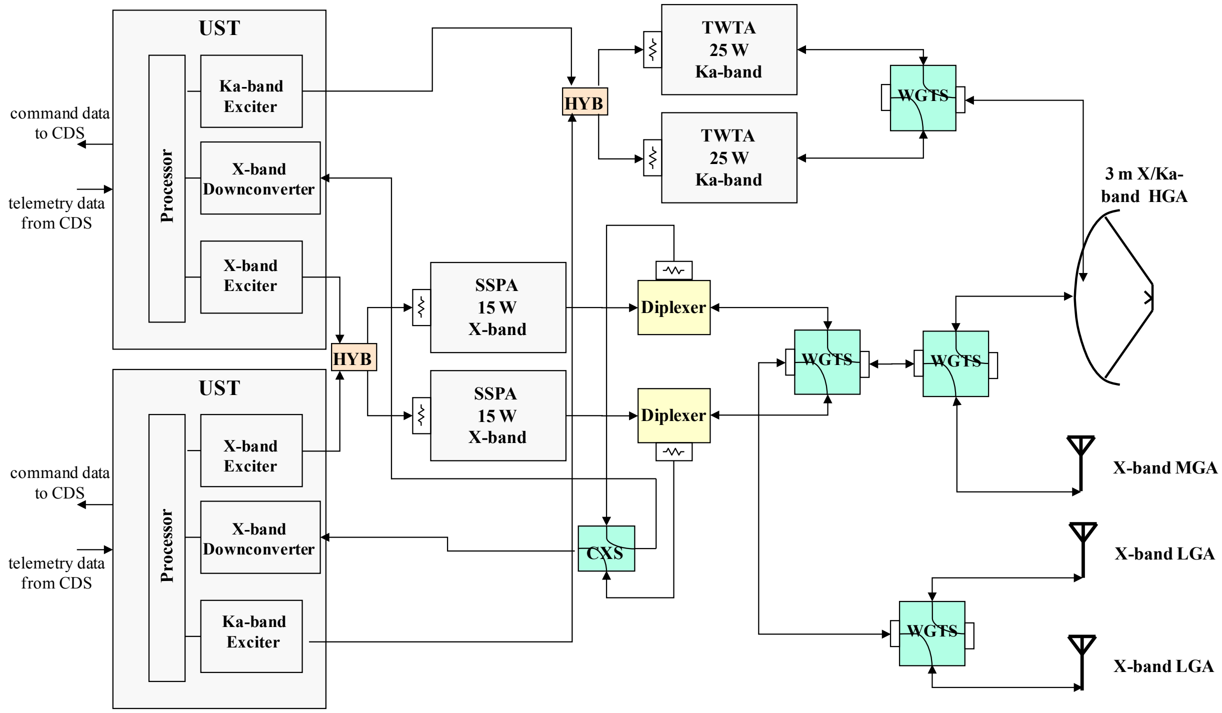


Figure 3-21. New Frontiers Relay Cruise Stage Block Diagram

Table 3-13. New Frontiers Relay Link Analysis

Link Description	MGA safe-mode downlink	HGA downlink	Lander to orbiter link (max range)
Frequency Band	X-band	Ka-band	X-band
Data Rate	10 bps	20 kbps	10 kbps
TRX Antenna	MGA, 5° off point	3 m HGA, 0.1° off point	3 m HGA, 0.25° off point
TRX Power (RF)	15 W	25 W	15 W
Range	7 AU	11 AU	71,000 km
RCV Antenna	70 m	34 m BWG	LGA (1 dBic)
Coding	Turbo 1/2, 1784 bit frame	Turbo 1/6, 8920 bit frame	LDPC coding (rate=1/2, k=1024)
Margin	3.4 dB	4.1 dB	6.0 dB

Key Mission Parameters

Table 3-14 provides a summary of the key mission parameters for the four options studied.

Table 3-14. Key Mission Parameters and Design Features

	Flagship	New Frontiers DTE	New Frontiers Relay Submersible	New Frontiers Relay Floating Lander
Flight System				
Launch mass (kg)	1,393 (carried by Flagship orbiter)	3,876	2,058	1,605
Total mission cost	$1.4 B (in-situ elements only)	$1.5 B	$1.5 B	$1.3 B
Radiation TID (krad)	22	16	17	17
Science				
Science goals	Titan lake composition and atmospheric interactions	Titan lake composition and atmospheric interactions	Titan lake composition	Titan lake composition
Key measurements	Lake composition vs. depth	Lake composition and atmospheric interactions	Lake composition vs. depth	Lake composition and atmospheric interactions
Total data volume (Gbits)	~8	~0.4	~2	~2
Mission Design				
Launch date	1-Jan-25	1-May-22	1-Jan-23	1-Jan-23
Launch vehicle	N/A	Atlas V 551	Atlas V 401	Atlas V 401
Launch mass allocation (kg)	N/A	3,883	2,645	2,645
Target body	Titan	Titan	Titan	Titan
Trajectory/orbit type	N/A	Ballistic with Earth gravity assist	Ballistic with two Earth and two Venus gravity assists	Ballistic with two Earth and two Venus gravity assists
Mission duration (months)	32-day surface operations	6-year cruise with 32-day science ops	9.25-year cruise with 2-day science ops	9.25-year cruise with 12-hour science ops
Key maneuvers	Atmospheric entry	Deep space maneuvers, gravity assists, atmospheric entry	Deep space maneuvers, gravity assists, atmospheric entry	Deep space maneuvers, gravity assists, atmospheric entry

	Flagship	New Frontiers DTE	New Frontiers Relay Submersible	New Frontiers Relay Floating Lander
Key mission phases	Atmospheric entry and descent, floating surface operations, lake descent, subsurface science operations	Spacecraft cruise atmospheric entry and descent, floating surface operations	Deep space maneuvers, gravity assists, atmospheric entry, surface science ops, lake descent, subsurface science ops, resurface	Deep space maneuvers, gravity assists, atmospheric entry, surface science ops
Instruments				
No. of instruments	8	6	4	3
Instrument types	Spectrometers, imaging cameras, pressure and temperature sensors, sonar	Spectrometer, imagers, turbidimeter, sounder, pressure and temperature sensors	Spectrometer, imagers	Spectrometer, imagers
Payload mass (kg) - CBE	67.9 (floating lander), 38 (submersible)	72.7 kg	41	38
Payload power (W)	150	150	150	150
Attitude Control System				
Pointing control (arcsec)	N/A	N/A	N/A	N/A
Pointing knowledge (arcsec)	N/A	N/A	N/A	N/A
Pointing stability (arcsec/s)	N/A	N/A	N/A	N/A
Stabilization type	N/A	3-axis (cruise stage)	3-axis (cruise stage)	3-axis (cruise stage)
Pointing technologies	N/A	Sun sensors, star trackers, IMUs (cruise stage)	Sun sensors, star trackers, IMUs (cruise stage)	Sun sensors, star trackers, IMUs (cruise stage)
In-situ sensors	Saturn camera (floating lander)	Sun sensor	N/A	N/A
Command and Data Handling				
Processor type	RAD750 (floating lander), event timer modules (submersible)	RAD750 (floating lander), MREU (cruise stage)	Event timer modules (submersible), RAD750 (cruise stage)	Event timer modules (floating lander), RAD750 (cruise stage)
Redundancy (hot, cold, single string)	Cold	Cold	Cold	Cold
Data compression	None	None	None	None

	Flagship	New Frontiers DTE	New Frontiers Relay Submersible	New Frontiers Relay Floating Lander
Telecommunications				
Bands	X-band (to orbiter), VHF (between in-situ elements)	X-band	X-band (to relay), Ka-band (to Earth)	X-band (to relay), Ka-band (to Earth)
Antenna type, size, and number	X-band patch LGA, VHF crossed dipole	0.75 m X-band HGA	X-band patch LGA (submersible), 3 m Ka-band HGA (cruise stage)	X-band Patch LGA (floating lander), 3 m Ka-band HGA (cruise stage)
Uplink rate (kbps)	32 (X-band), 0 (VHF)	1 (X-band from Earth)	32 (X-band relay), 2 (X-band from Earth)	32 (X-band relay), 2 (X-band from Earth)
Downlink rate (kbps)	2000 (X-band relay), 32 (VHF)	0.44 (X-band to Earth)	2000 (X-band relay), 20 (Ka-band to Earth)	2000 (X-band relay), 20 (Ka-band to Earth)
Gimbaled? (Y/N)	No	Yes	No	No
Power				
EOL power (W)	295	301	289 (cruise stage), 0 (submersible)	289 (cruise stage), 0 (floating lander)
Power source (solar, RPS)	RPS	RPS	RPS	RPS
RPS type (ASRG, MMRTG)	ASRG	ASRG	ASRG	ASRG
RPS quantity	Two (floating lander)	Two (floating lander)	Two (cruise stage)	Two (cruise stage)
Total RPS power (W)	260	266	260	260
Battery storage size(s) (A-hrs)	30 (floating lander), 100 (submersible)	30	100 (submersible), 30 (cruise stage)	100 (floating lander), 30 (cruise stage)
Battery type(s)	Advanced Li-Ion secondary (floating lander), Li-CFx primary (submersible)	Advanced Li-Ion	Li-CFx (submersible), advanced Li-Ion (cruise stage)	Li-CFx (floating lander), advanced Li-Ion (cruise stage)
Battery quantity	4 on both elements	7 (floating lander) 3 (cruise stage)	4 (submersible), 3 (cruise stage)	3 (floating lander), 2 (cruise stage)
Propulsion				
No. of prop systems	N/A	1	1	1

	Flagship	New Frontiers DTE	New Frontiers Relay Submersible	New Frontiers Relay Floating Lander
Type(s) of system(s)	N/A	Dual-mode bipropellant system (cruise stage)	Pressurized monopropellant system (cruise stage)	Pressurized monopropellant system (cruise stage)
Total delta V (m/s)	N/A	2575	520	400
Propellant type	N/A	NTO and N_2H_4	N_2H_4	N_2H_4
Propellant mass(es) (kg)	N/A	1086 (oxidizer), 1109 (fuel)	702 (fuel)	515 (fuel)
Structure				
Primary structural mass (kg) - CBE	109 (floating lander), 59.2 (submersible)	108 (floating lander), 156 (heatshield / backshell), 192 (cruise stage)	55 (submersible), 136 (heatshield / backshell), 133 (cruise stage)	57 (floating lander), 109 (heatshield / backshell), 148 (cruise stage)
Structure material (Aluminum, Composites, etc)	Aluminum	Aluminum	Aluminum	Aluminum
Number of articulated structures	1 (floating lander), 0 (submersible)	1 (floating lander)	0	0
Number of deployable structures	3 (floating lander), 3 (submersible)	1 (floating lander)	1 (submersible)	1 (floating lander)
Mechanisms (type, quantity)	Antenna and instrument mast, submersible release, sink rate controller, module separation, solid sampling tool	HGA gimbal, instrument mast	Floatation tank flooder, module separation, solid sampling collector	None
Aeroshell diameter (m)	2.6	3	2.1	2.1
Thermal				
Thermal control method	Passive	Passive	Passive	Passive
Design drivers	Titan surface environment (90 K)	Titan surface environment (90 K)	Titan surface environment (90 K)	Titan surface environment (90 K)
Radiator area (m^2)	N/A	N/A	N/A	N/A
Thermal control technologies	Vacuum getters, MLI insulation, RHUs	Vacuum getters, aerogel, and MLI insulation	Vacuum getters, MLI insulation, RHUs	Vacuum getters, MLI insulation, RHUs

Concept of Operations and Mission Design

The Team X study covered four options for the Titan Lake Probe mission, three of which required mission design input. The remaining option (Option 1), based upon the Flagship TSSM design, was to cost only the entry system and landed hardware; therefore, the mission design is not reflected here. Options 2 and 3 are variations meant to fit within a New Frontiers cost cap. Option 2 is a DTE telecom, with the carrier simply dropping the EDL/lander vehicle and flying by. Options 3 and 4 require the carrier to relay the data from the lander. These three options are all chemical-mission designs.

Option 2: Six-Year Cruise with Earth Gravity Assist

Figure 3-22 provides an illustration of the trajectory for Option 2, which would require a total of a little less than 2.6 km/s spacecraft delta V, expended over three DSMs to implement. Table 3-15 provides the timeline and delta-V budget for a May 2020 launch and May 2026 arrival.

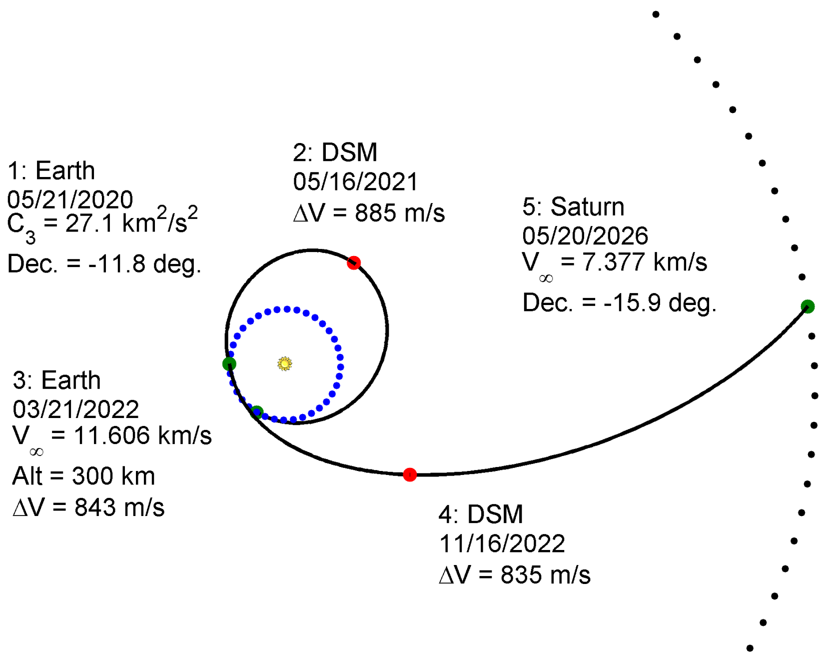


Figure 3-22. Trajectory—Option 2

Table 3-15. Timeline and Delta-V Budget—Option 2

Event	L + days	Delta-V (m/s)
Launch	0	15
DSM 1	360	885
Earth flyby	670	5
DSM 2	671	843
DSM 3	909	835
Approach nav	2,160	5
Arrive Saturn/separate lander	2,190	2
Total	**–**	**2,590**

Table 3-16. Tracking Schedule—Option 2

Support Period		Antenna Size (m)	Service Year	Hours per Track	No. Tracks per Week	No. Weeks Required	Pre-, Post-Config. (hrs)	Total Time Reqd. (hrs)
No.	**Name (description)**							
1	Launch and operations	34 BWG	2022	8	21.0	2.0	42.00	378.0
2	Launch and operations	34 BWG	2022	8	14.0	2.0	28.00	252.0
3	Cruise to Earth flyby—cruise	34 BWG	2022	8	1.0	103.0	103.00	927.0
4	Cruise to Earth flyby—TCMs	34 BWG	2022	8	7.0	2.0	14.00	126.0
5	Cruise to Earth flyby—annual health checks	34 BWG	2022	8	7.0	1.0	7.00	63.0
6	Earth Flyby—initial encounter	34 BWG	2022	8	21.0	1.0	21.00	189.0
7	Cruise to Saturn—cruise	34 BWG	2022	8	1.0	205.0	205.00	1845.0
8	Cruise to Saturn—TCMs	34 BWG	2022	8	7.0	4.0	28.00	252.0
9	Cruise to Saturn—annual health checks	34 BWG	2022	8	7.0	3.0	21.00	189.0
10	Encounter—initial encounter	34 BWG	2022	8	21.0	1.0	21.00	189.0
11	Encounter—extended encounter	34 BWG	2022	8	7.0	1.0	7.00	63.0

The launch vehicle would be an Atlas V 551. While no launch period or launch window analysis was done, in general, allowing 1.5 to 2 units of C3 above the optimum would provide for a two- to three-week launch period. Thus, assuming a C3 of 28 km^2/s^2 specifies the maximum required C3, the Atlas 551's capability is 3750 kg. With a single earth gravity assist, launch opportunities to fly similar missions would repeat annually, with small changes in C3 and delta-V requirements. Building margin into the design to accommodate that possibility is beyond the scope of this study, but should incur only minor changes to the values shown here.

Table 3-16 provides the tracking schedule for Option 2. During a 16-day Titan orbit period, there would be a 3-day DTE communications window with the lander. The total communications time over the 32-day mission would therefore be one week (item 10). While a frequency of one pass / week is common during interplanetary cruise, the two long periods of quiescent cruise (items 3 and 7) are routine enough that the tracking frequency can be reduced to every other week (0.5 pass / week) with a proportional savings in cost.

Options 3 and 4: Venus-Earth-Venus-Earth Gravity Assist

Options 3 and 4 share the same basic trajectory for the flight to Titan. This trajectory trades flight time for delta V, which would facilitate the accommodation of the higher delta V required to support the separation between carrier and lander for the relay (Figure 3-23). The result is a dramatic reduction in delta V implemented by the spacecraft, though with a more complex mission involving multiple flybys along with longer flight time. Table 3-17 provides a summary of delta V. Launch would be scheduled for January 2023 with Saturn/Titan arrival in May 2032. A launch C3 of 13.5 km^2/s^2 would cover a reasonable launch period, though as in Option 2, a launch period/window analysis has not been completed and is left for further study. Using an Atlas V 511 would provide a launch mass capability of 2895 kg.

The 250 m/s divert maneuver is assumed to occur three months prior to Titan flyby. This would allow for a 2-day separation between the probe entry and the relay flyby.

As with Option 2, the periods of longer cruise in this timeline (items 3 and 16) would be amenable to cost savings if weekly tracking passes are reduced to every other week. Table 3-18 provides a nominal tracking schedule.

Table 3-19 compares the two options discussed in this section.

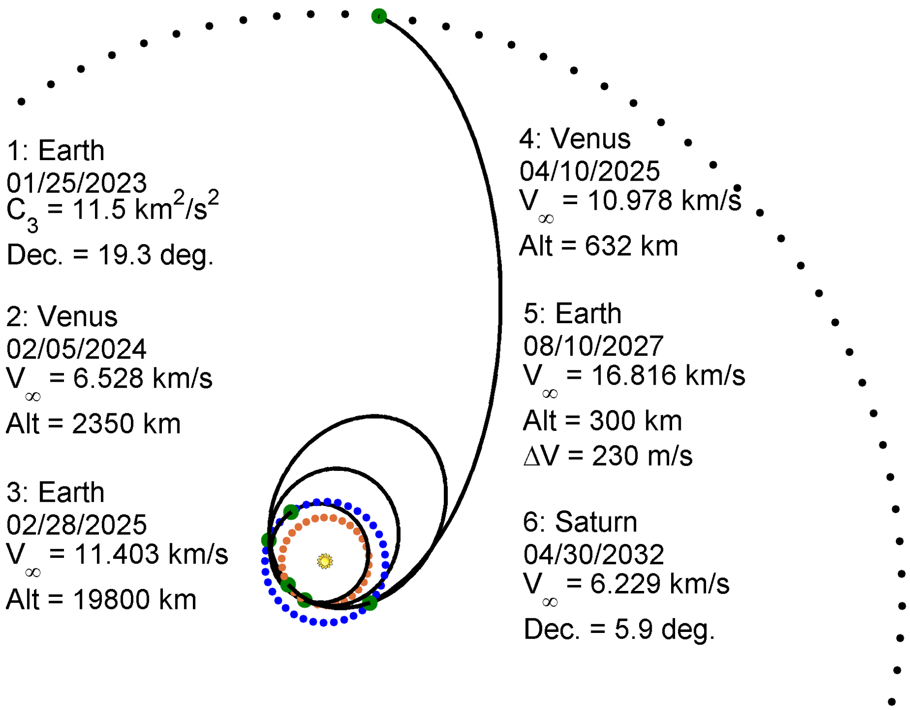


Figure 3-23. Trajectory—Options 3 and 4

Table 3-17. Timeline and Delta-V Budget—Option 3

Event	L + days	Delta-V (m/s)
Launch	0	0
Venus flyby	376	5
Earth flyby	765	5
Venus flyby	806	5
Earth flyby	1658	5
DSMs	TBS	250
Arrive Saturn/separate lander/divert bus	3385	250
Total	–	**520**

Table 3-18. Tracking Schedule—Option 3

Support Period		Antenna Size (m)	Service Year	Hours per Track	No. Tracks per Week	No. Weeks Required	Pre-, Post-Config. (hrs)	Total Time Reqd. (hrs)
No.	Name (description)							
1	Launch and operations	34 BWG	2023	8	21.0	2.0	42.00	378.0
2	Launch and operations	34 BWG	2023	8	14.0	2.0	28.00	252.0
3	Cruise to Venus flyby—cruise	34 BWG	2023	8	1.0	103.0	103.00	927.0
4	Cruise to Venus flyby— TCMs	34 BWG	2023	8	7.0	2.0	14.00	126.0
5	Cruise to Venus flyby—annual health checks	34 BWG	2023	8	7.0	1.0	7.00	63.0
6	Venus flyby—initial encounter	34 BWG	2023	8	7.0	1.0	7.00	63.0
7	Cruise to Earth flyby—cruise	34 BWG	2023	8	1.0	26.0	26.00	234.0
8	Earth flyby—initial encounter	34 BWG	2023	8	7.0	4.0	28.00	252.0
9	Earth flyby—extended encounter	34 BWG	2023	8	7.0	1.0	7.00	63.0
10	Cruise to Venus flyby— cruise	34 BWG	2023	8	1.0	26.0	26.00	234.0
11	Venus flyby—initial encounter	34 BWG	2023	8	7.0	4.0	28.00	252.0
12	Venus flyby—extended encounter	34 BWG	2023	8	7.0	1.0	7.00	63.0
13	Cruise to Earth flyby—cruise	34 BWG	2023	8	1.0	26.0	26.00	234.0
14	Earth flyby—initial encounter	34 BWG	2023	8	7.0	4.0	28.00	252.0
15	Earth flyby—extended encounter	34 BWG	2023	8	7.0	1.0	7.00	63.0
16	Cruise to Saturn—cruise	34 BWG	2023	8	1.0	244.0	244.00	2196.0
17	Cruise to Saturn—TCMs	34 BWG	2023	8	7.0	4.0	28.00	252.0
18	Cruise to Saturn—annual health checks	34 BWG	2023	8	7.0	3.0	21.00	189.0
19	Prep for Titan EDL and science phase—cruise	34 BWG	2023	8	2.0	26.0	52.00	468.0
20	Titan EDL and science phase—initial encounter	34 BWG	2023	8	21.0	1.0	21.00	189.0
21	Titan EDL and science phase—extended encounter	34 BWG	2023	8	7.0	1.0	7.00	63.0

Table 3-19. Option Trajectory Comparison

Option	Delta V (m/s)	Orbit/Trajectory	Comments
2	2,575	Earth-Earth-Saturn	1. 6-year flight time 2. ~1 AU minimum solar distance 3. Launch opportunities using similar trajectory every year
3	520	Earth-Venus-E-V-E-S	1. 9.3-year flight time 2. 0.66 AU minimum solar distance 3. Launch opportunities no more frequently than Venus-Earth synodic period (1.6 years)

Entry, Descent, and Landing (EDL) Concept of Operations

Mission Architecture

The EDL architectures for the Titan Lake Probe study were developed for the four options characterized in this report. Table 3-20 provides the entry parameters used for each option in the EDL analysis.

The four mission options would have significantly different surface elements and science payloads. However, in terms of EDL architecture, all options would employ identical aeroshell geometry and parachute designs that would be scaled for the different entry masses. The Titan Lake Probe EDL design utilizes components of the proven Huygens Probe flight architecture. The probe in each option would consist of a submersible and/or floating lander element packaged in a 60° sphere-cone aeroshell separated by a heatshield (forebody) and backshell (aft cover). A preliminary analysis was done in order to identify the optimum heatshield geometry for the Titan probe. Since the gas composition of Titan's atmosphere is fairly similar to Earth, it was concluded based on the NACA-TR-1135 report that the bow shock would fail to attach at the capsule's nose with heatshield sphere-cone angles greater than 60°. Similar to the Huygens Probe, the design used phenolic silica fiber for the heatshield's thermal protection material (TPS). The nose radius for the heatshield was kept at Rn = 1.25 m.

Based on the Huygens Probe EDL sequence, the parachute system would employ a drogue/main chute architecture, where the total number of chutes would be two. These are both disk-gap-band (DGB) chutes with coefficient of drag (Cd) ~0.4 to 0.7 and average angle of attack (AOA) of ±10° during descent. The reference diameters of the pilot and main chutes were scaled accordingly in order to accommodate various payload configurations (see Table 3-20). With the exception of Option 1, Options 2–4 would undergo a very similar EDL sequence of events (i.e., hypersonic entry phase, drogue chute, heatshield separation, main chute, touchdown) as illustrated in Figure 3-24. Option 1 was not to be costed in the final study and therefore was not analyzed in great detail. The remaining portion of this section provides details of Options 2–4 only.

The entry interface with the atmosphere of Titan would occur at ellipsoidal altitude of 1500 km. The capsule would hypersonically decelerate to an altitude of 150–160 km, where the drogue DGB chute would be triggered at Mach 1.5. The drogue chute would provide the capsule attitude stability through the sonic transition phase. At 2.5 seconds after drogue chute deployment, the aft cover (backshell) would separate and pull the main DGB chute, which would remain attached for the terminal descent portion of the trajectory. The heatshield would be separated at Mach <0.6. The total descent time from entry epoch to Titan lake touchdown is estimated to be ~2 hours and 15 minutes.

Table 3-20. Entry Parameters

	Option 1	**Option 2**	**Option 3**	**Option 4**
Entry mass (kg)	1387	867	648	499
Aeroshell diameter (m)	2.6	3.0	2.1	2.1
Drogue chute diameter (m)	–	2.5	1.5	1.5
Main chute diameter (m)	–	5.0	4.0	4.0

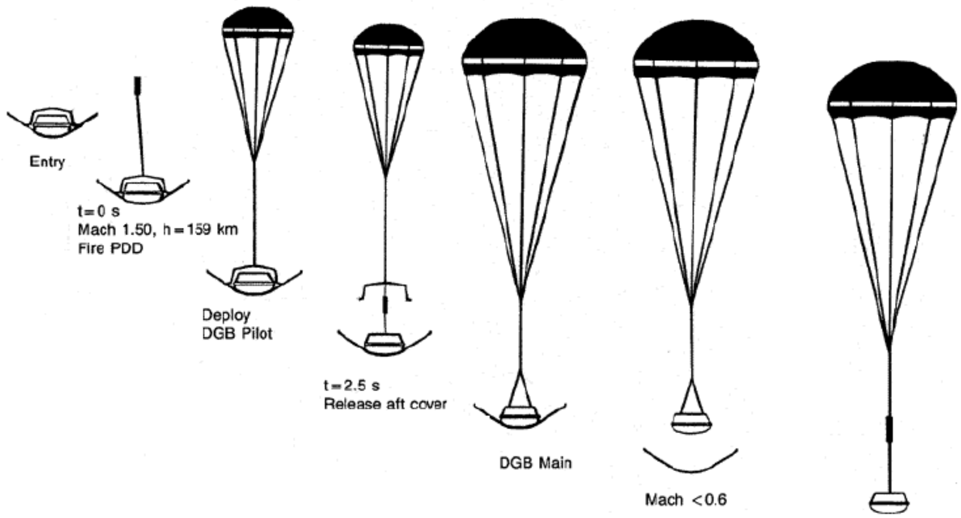


Figure 3-24. Entry, Descent, and Landing Timeline

Landing Site Selection

A series of parametric studies were conducted to establish the feasibility of the proposed landing architectures and to perform preliminary landing site selection. Two lakes, Ontario Lacus (in the Southern hemisphere) and Kraken Mare (in the Northern hemisphere), were identified as potential EDL targets. Figures 3-25 and 3-26 illustrate a view of the Titan polar map along with lakes sizes and geometries.

Analysis has shown that Kraken Mare, due to its size, could potentially accommodate any typical EDL trajectory design. The admissible maximum landing ellipse for Kraken Mare could be as large as 400 × 800 km. Ontario Lacus would require significantly more accurate landing precision, in which the landing ellipse should not exceed 150 × 80 km. This critical aspect of the design was closely investigated for Options 2–4, since landing in the Southern hemisphere could offer lighting and telecom advantages.

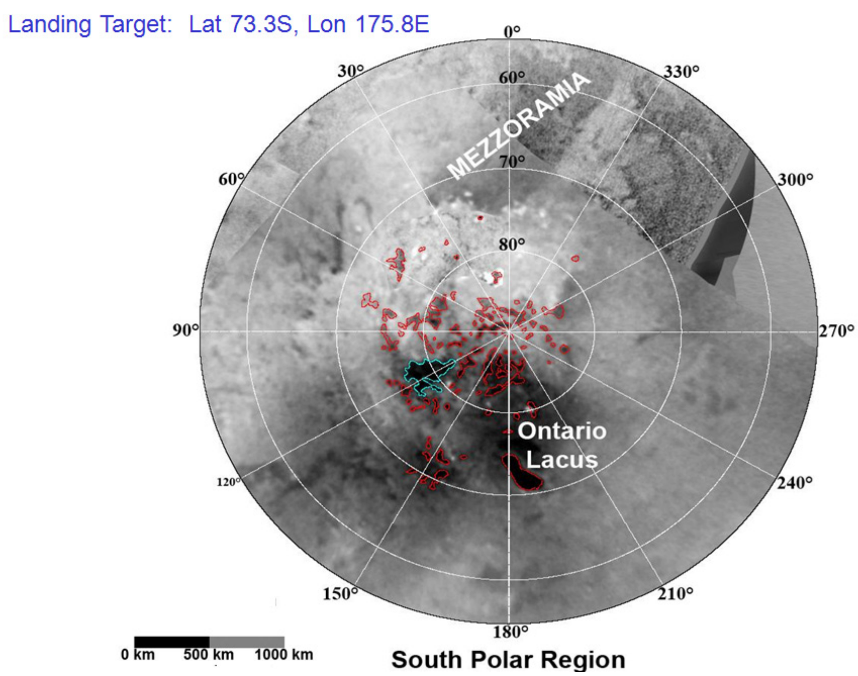


Figure 3-25. Landing Target—Ontario Lacus

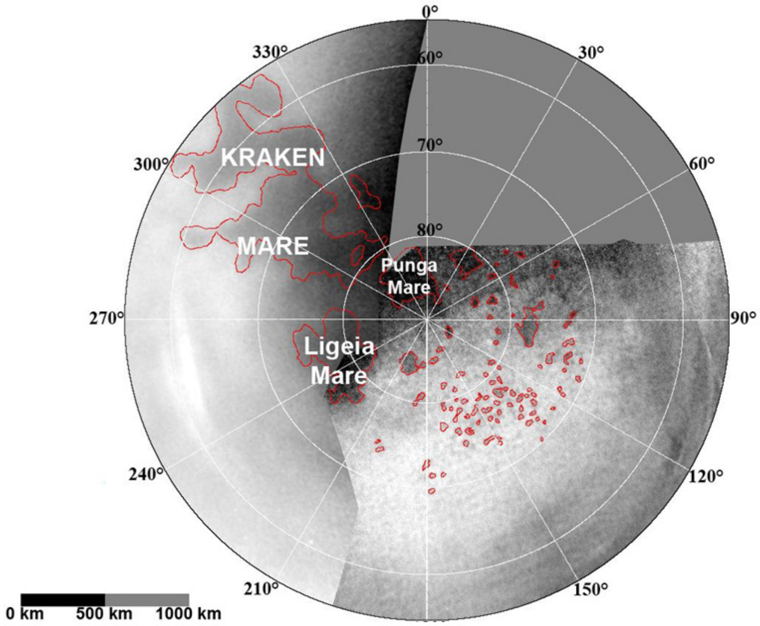


Figure 3-26. Landing Target—Kraken Mare

Option 2 (Landing Precision)—This option assumes that the spacecraft would have a simple cruise stage during the outer-planetary portion of the trajectory. After performing a sequence of trajectory correction maneuvers (TCMs) for EDL targeting, the entry vehicle would separate from the spacecraft at entry minus 15 minutes. This architecture would potentially minimize the navigational errors prior to Titan entry condition. A 3-sigma high-entry flight path angle (EFPA) uncertainty of ±0.15° was assumed for the EDL Monte Carlo analysis. The B-plane parameters of Titan entry states were adjusted in order to target the center of Ontario Lacus (latitude 73.3S, longitude 175.8E). The actual entry states in the Earth Mean Equator of J2000 (EMEJ2000) coordinate frame used in the trajectory simulation are summarized in Table 3-21.

A fairly steep EFPA of −70° was chosen in order to achieve smaller dispersions projected on the B-plane, and to help minimize the wind drift during EDL. Certain assumptions had to be made about the wind pattern on Titan for the set of Monte Carlo trajectory simulation runs. Based on the wind profile reconstructed from the Huygens Probe descent (see Figure 3-27), it was decided to simulate the wind dispersions as ±0.5× magnitude of east-west Huygens nominal wind profile. Figure 3-28 illustrates the Monte Carlo results along with the wind dispersions.

Table 3-21. Entry States in EMEJ2000

Epoch	2028-Jan-02 07:38:26.7015
Coordinate frame (frame +005)	EME J2000 Titan (body 606) centered
Radius	4275.00129262423 (km)
V-inf magnitude	6.14355767798584 (km/s)
V-inf decl/latitude	-11.2520549059696 (deg)
V-inf RtAsc/longitude	355.818071115953 (deg)
B-plane angle	78.635 (deg)
EFPA (at R = 4275 km)	-70 (deg)

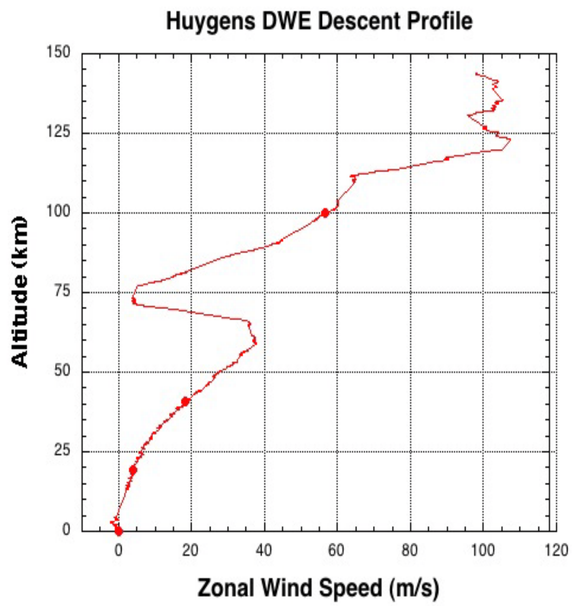


Figure 3-27. Huygens Descent Profile

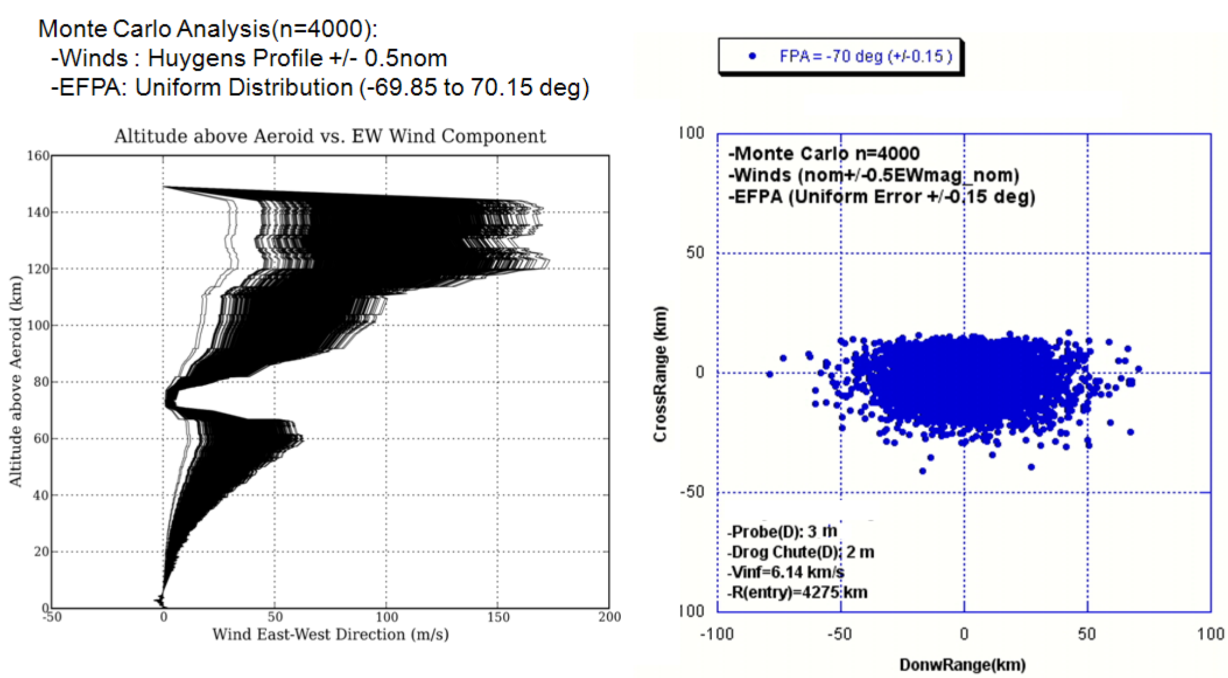


Figure 3-28. Monte Carlo Analysis ±0.5× Magnitude of East-West Huygens Wind Profile

As can be seen from the scatter plot in Figure 3-28, the Option 2 lake lander barely satisfies the landing precision constraints imposed by the maximum geometrical dimensions of Ontario Lacus. However, very little is known about the wind characteristics of Titan's atmosphere. In order to stress the EDL system, significantly larger wind dispersions were assumed for subsequent Monte Carlo simulations. With the revised wind assumptions of ±0.8× magnitude of east-west Huygens nominal wind profile, the landing ellipse increased by ±30 km (see Figure 3-29), which would no longer satisfy the landing ellipse requirements of Ontario Lacus.

If a more conservative approach to the EDL trajectory design were adopted, then the prevailing east-west wind component should be substituted by the uniform 0–360° distribution in azimuth measured from the north. The Monte Carlo results would suggest that the landing footprint should be 300 × 300 km (see Figure 3-30). This particular EDL scenario would be extremely taxing for the Ontario Lacus target, yet the lander of Option 2 could easily achieve the desired target at latitude 70° N of Kraken Mare. With very limited scientific data available on Titan's zonal winds, it was decided to take the more conservative approach in the selection of potential landing sites. Therefore, the remaining portion of the EDL analysis focused solely on Kraken Mare as the primary target for Options 2–4.

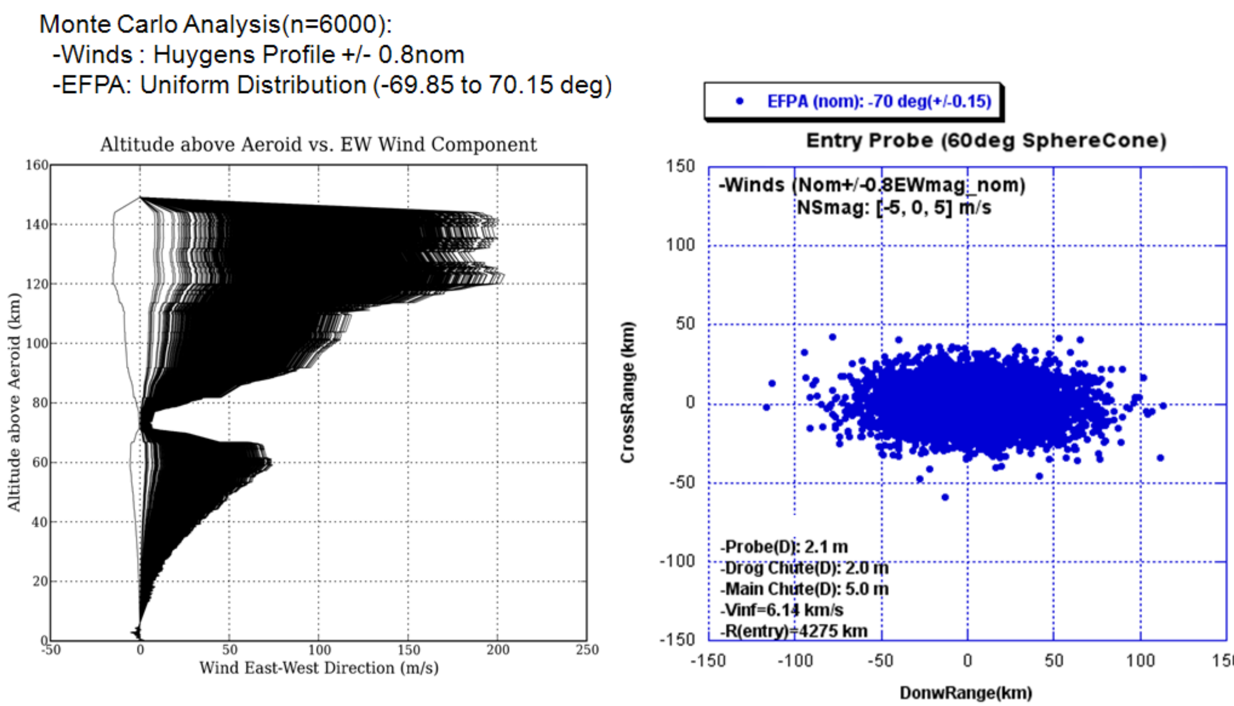


Figure 3-29. Monte Carlo Analysis ±0.8× Magnitude of East-West Huygens Wind Profile

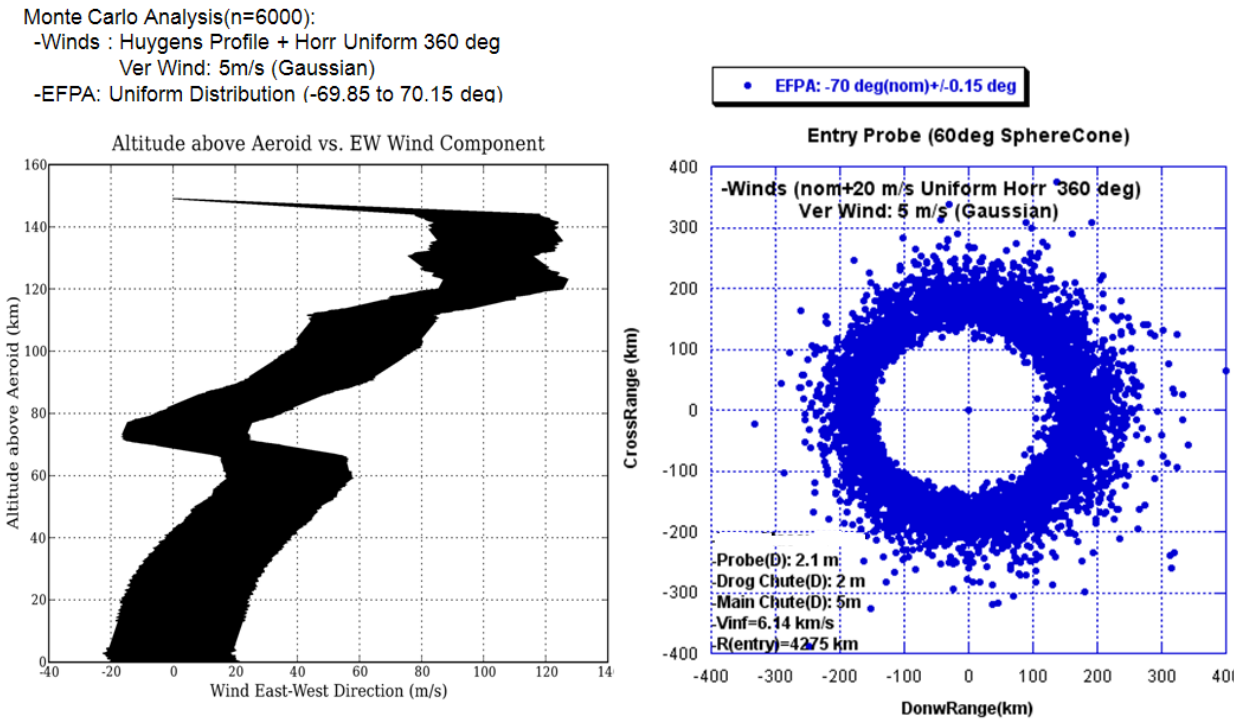


Figure 3-30. Monte Carlo Analysis 0–360° Uniform Wind Distribution

Options 3 and 4 (Landing Precision)—In contrast with Option 2, Options 3 and 4 would employ a significantly different Titan approach strategy. The outer-planetary trajectory design suggests that the entry vehicle must be released from the spacecraft carrier at entry minus 105 days in order to accommodate a sufficient separation between in-situ vehicle arrival and flyby of the relay spacecraft. An imposed constraint on the Titan closest probe release date of entry minus 105 days would be dictated by the spacecraft ΔV requirements for the flyby retargeting maneuver. By taking into consideration all of these requirements, the entry vehicle EFPA uncertainty upon entry state would increase from ±0.15° to ±2.5°. With such a poor EFPA accuracy, Options 3 and 4 would not be able to target Ontario Lacus. The trajectory design had to be adjusted in order to target Kraken Mare, which resulted in a slight increase of the approach *Vinf* magnitude from 6.14 km/s to 6.47 km/s. Based on the extensive Monte Carlo analysis produced for Option 2, it was decided to adopt a ±2.5° uniform distribution and ±0.8× magnitude of east-west Huygens nominal wind profile for the new set of Monte Carlo runs. The results shown in Figure 3-31 clearly illustrate the precision penalty associated with the given EFPA error. However, the landing ellipse would not violate Kraken Mare target constraints.

Figure 3-32 illustrates the results of a parametric study that investigated the trend of the maximum G-loads, experienced by the entry probe in the hypersonic phase of the EDL, versus the entry ballistic coefficient of the sized vehicle. This analysis shows that the deceleration loads should remain well below the ASRG quasi-steady acceleration requirement of 18 G.

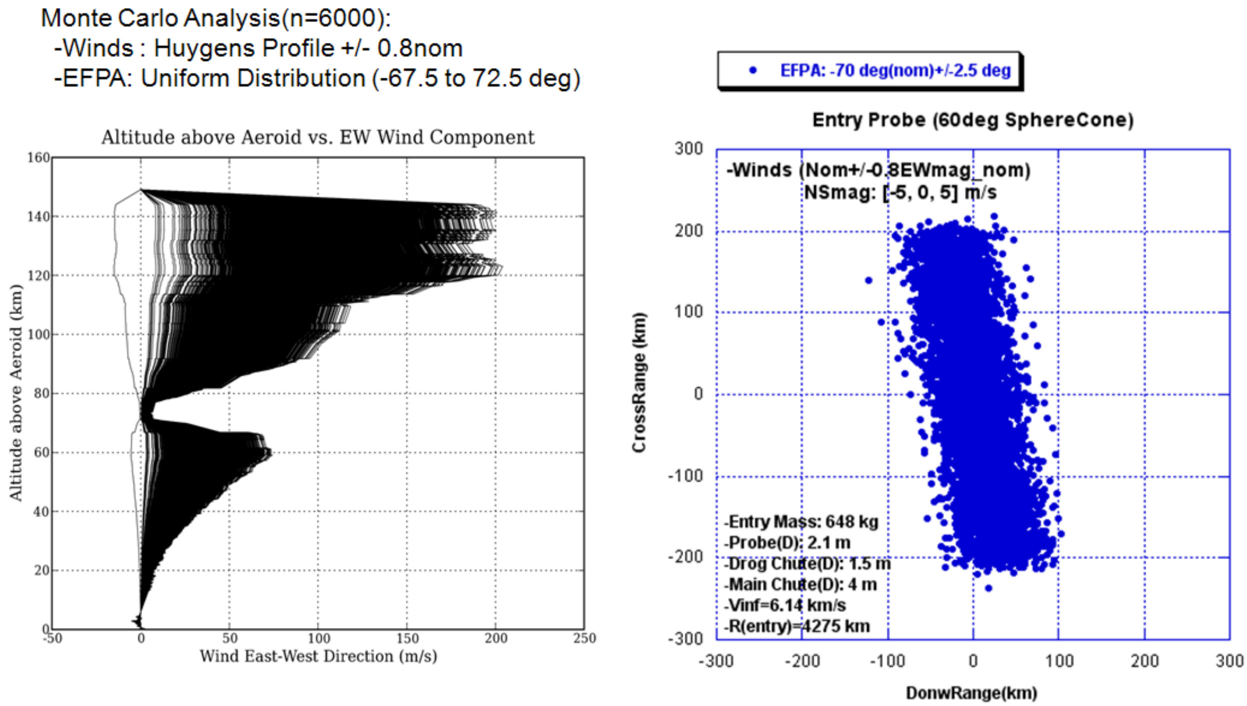


Figure 3-31. Monte Carlo Analysis ±2.5° Uniform Distribution and ±0.8× Magnitude of East-West Huygens Wind Profile

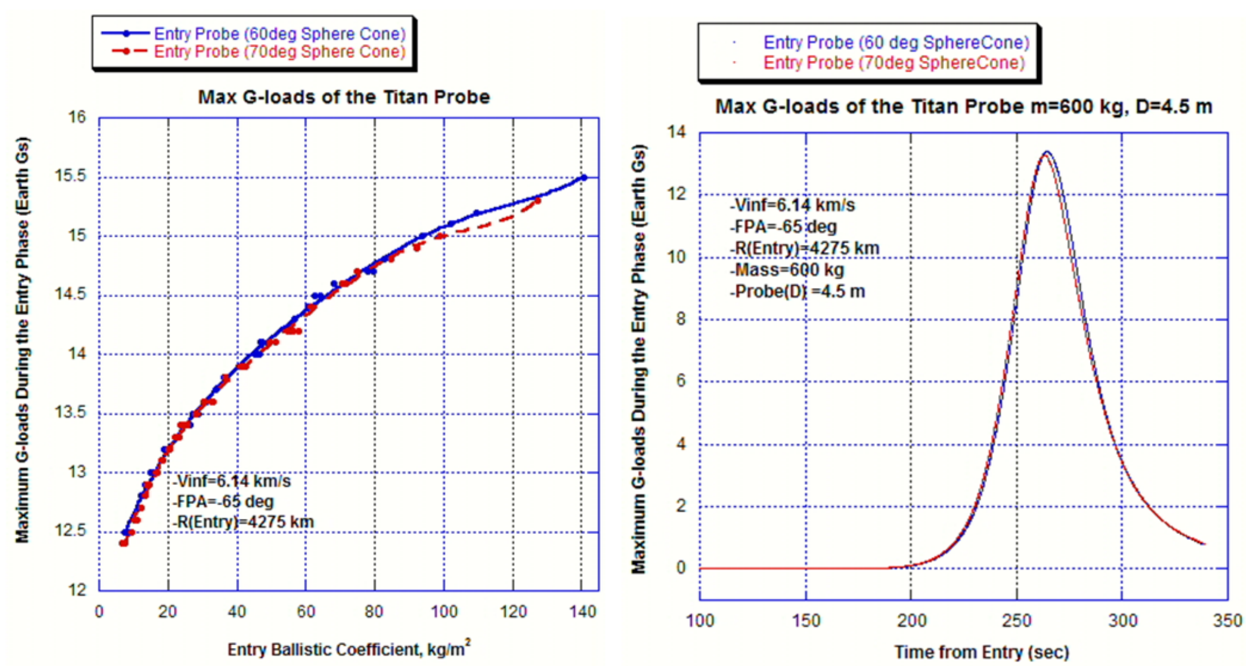


Figure 3-32. Titan Probe G-Loadings

Surface Concept of Operations—Data and Power Budgets

For operations on the surface, a timeline was created for each vehicle (i.e., the floating lander, submersible, or both) for each of the four options. This timeline was then used to determine when each of the instruments in the science payload for the floating lander and/or the submersible would be on, and how many observations the instrument would take. Data volume calculations were made on the basis of the data volume generated by a science instrument for one specific observation, or by using a data rate corresponding to data generated by the instrument on a continuous basis. A table of telemetry calculations is provided for each option showing how these data volumes were calculated. It should be noted that in all cases, it was assumed that there would be a 7% overhead on science data for the formatting of this data to the CCSDS standards, including overhead for the use of the CCSDS File Delivery Protocol (CFDP). For some studies, a margin can be placed on the science data volume. However, for this study, no margin was added (i.e., 0%).

Power calculations were also performed for the instruments, subsystems, and other loads placed on the power system of the floating landers and/or submersibles. Results are provided in a table for each of the options, as well as a plot showing battery depth of discharge over time. For the purposes of the calculations in this analysis, it was assumed that there is a 100% efficiency for any voltage conversions that are necessary as part of the architecture of the power system. However, a 15% tax was placed on each electrical power load, which includes power needed by the power system, including harness and other losses. Furthermore, a 30% uncertainty was assumed in the power calculations; this amount was added to the power required by each load as a margin. Not shown in the power calculations table are other losses, specifically an assumption that there is 90% efficiency for energy placed into the battery and 95% efficiency for energy taken out of the battery.

Option 1: Flagship Floating Lander and Submersible

The timeline for this option is shown in Table 3-22. Option 1 would include both a floating lander and a submersible element in the landed hardware. This table indicates when each instrument would be on and taking data. It also indicates how many observations would be taken during the particular period (for observation-based instruments) or what fraction of time the instrument would be on for the time period (for data rate–based instruments).

Data Volume Simulations. Telecommunications columns in Table 3-22 also indicate periods when data could be transferred from the submersible to the floating lander via the VHF link, and from each of these elements through the X-band data relay to the Flagship orbiter. Communications to the orbiter would only be available for a limited amount of time, once each 32 days as the orbiter is in a 2:1 orbital resonance with Titan around Saturn. These communications windows are only open for a few hours each 32 days. However, the communications rates could get quite high, and the total data volume that could be transferred from the surface of Titan to the orbiter is approximately 3.5 Gbits for each pass.

The information presented in Table 3-22 was used to calculate a simulation of the amount of data generated over time by the instrument suite with data volumes or data rates indicated in Table 3-23 and Table 3-24. Results of these simulations for the floating lander are shown in Figure 3-33 and for the submersible in Figure 3-34.

Table 3-22. Timeline—Option 1

Event	Time (Day)	Time (Hrs)	Tele Comm to Relay	Tele Comm to Floater	Floater: Hi res GC-GC MS	Floater: LPP	Floater: Echo	Floater: Turbid	Floater: Mast TDL	Floater: Mast wind	Floater: DISR	Floater: Des Cam	Floater: Surf Cam	Floater: Mag	Sub: Lo res GC-GC MS	Sub: FTIR	Sub: LPP	Sub: Echo	Sub: Turbid
															Obs	Obs	Obs	Obs	
	D1	0																	
		1																	
		2																	
		3																	
		4																	
		5																	
		6																	
		7																	
		8	Floater																
		9																	
start aerial descent		10			36						767	5							
		11			36														
splashdown		12											96						
		13																	
		14			2														
		15			1										7 MS runds 2016 Kb each				
		16																	
		17																	
		18																	
		19																	
		20																	
		21																	
start sub descent		22														204	2000		
		23														204	2000		
Sub reaches bottom	D2				1 Run per day	Continuous	410 over period		600 per hour				3 Sets per day, 93 sets total	Continuous	14 runs in total, each is 2016kb data	14 obs total	1 obs each hour	1 obs each hour	
	D3																		
	D4																		
	D5																		
	D6																		
	D7																		
	D8																		
	D9																		
	D10																		
	D11																		
	D12																		
	D13																		
	D14																		
	D15																		
	D16																		
	D17																		
	D18																		
	D19																		
	D20																		
	D21																		
	D22																		
	D23																		
	D24																		
	D25																		
	D26																		
	D27																		
	D28																		
	D29																		
	D30																		
	D31																		
sub ascent	D32	0																	
		1																	
		2																	
		3																	
		4																	
		5																	
		6																	
		7																	
		8																	
		9																	
		10																	
		11																	
		12																	
		13	Sub																
		14																	
		15	Floater																
		16																	
		17																	
		18																	
		19																	
		20																	
		21																	
		22																	
		23																	

Table 3-23. Floating Lander Telemetry Calculations—Option 1

Instrument	Data Rate (Kbps) or Observation Size (Kbits)	Observation or Constant Rate	Instrument Hourly or Observation Data Volume (Mbits)	Formatting Overhead (Mbits)	Hourly or Observation Data Volume w/Overhead (Mbits)	Margin Data Volume (Mbits)	Hourly or Observation Data Volume w/Margin (Mbits)
				Overhead 7%		Margin 0%	
Descent GC-GC/MS	15000.0	Obs	15.000	1.1	16.1	0.0	16.1
High Res GC-GC/MS	1000000.0	Obs	1000.000	70.0	1070.0	0.0	1070.0
Surface MS	15,555.6	Obs	15.556	1.1	16.6	0.0	16.6
Mass Spec Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
			0.000	0.0	0.0	0.0	0.000
Echo Sounder	0.016	Obs	0.000	0.0	0.0	0.0	0.000
LPP Package	0.033	Rate	0.119	0.0	0.1	0.0	0.127
LPP Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
Turpidimeter			0.000	0.0	0.0	0.0	0.000
Magnetometer	0.063	Obs	0.000	0.0	0.0	0.0	0.000
Mast Mtd Instr	0.191	Obs	0.000	0.0	0.0	0.0	0.000
Mast Mtd Instr Warm-Up	0.008	Obs	0.000	0.0	0.0	0.0	0.000
DISR Package	70.92	Obs	0.071	0.0	0.1	0.0	0.076
DISR Solar Aureole	14.40	Obs	0.014	0.0	0.0	0.0	0.015
DISR Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
Descent Camera (2)	6292.0	Obs	6.292	0.4	6.7	0.0	6.732
Descent Camera Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
Surface Cameras (3)	3146.0	Obs	3.146	0.2	3.4	0.0	3.366
Surface Cameras Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
			0.000	0.0	0.0	0.0	0.0
			0.000	0.0	0.0	0.0	0.0
			0.000	0.0	0.0	0.0	0.0
Engineering Data High	1.0	Rate	3.600	0.3	3.9	0.0	3.9
Engineering Data Low	0.4	Rate	1.440	0.1	1.5	0.0	1.5

Table 3-24. Submersible Telemetry Calculations—Option 1

Instrument	Data Rate (Kbps) or Observation Size (Kbits)	Observation or Constant Rate	Instrument Hourly or Observation Data Volume (Mbits)	Formatting Overhead (Mbits)	Hourly or Observation Data Volume w/Overhead (Mbits)	Margin Data Volume (Mbits)	Hourly or Observation Data Volume w/Margin (Mbits)	Data Volume Compression Factor	Instrument Compressed Data Volume per Hour or Observation (Mbits)
				Overhead 7%		Margin 0%			
GC-GC/MS	2016.0	Obs	2.016	0.1	2.2	0.0	2.2	1	2.1571
GC-GC/MS Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.0	1	0.0308
MS	2016.0	Obs	2.016	0.1	2.2	0.0	2.2	1	2.1571
FTIR Spectrometer	144.0	Obs	0.144	0.0	0.2	0.0	0.154	1	0.1541
FTIR Spec Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
LPP	0.026	Obs	0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
Echo Sounder	0.016	Obs	0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
Turpidimeter			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
Engineering Data	0.5	Rate	1.800	0.1	1.9	0.0	1.9	1	1.9260
Engineering Data	0.01	Rate	0.036	0.0	0.0	0.0	0.0	1	0.0385

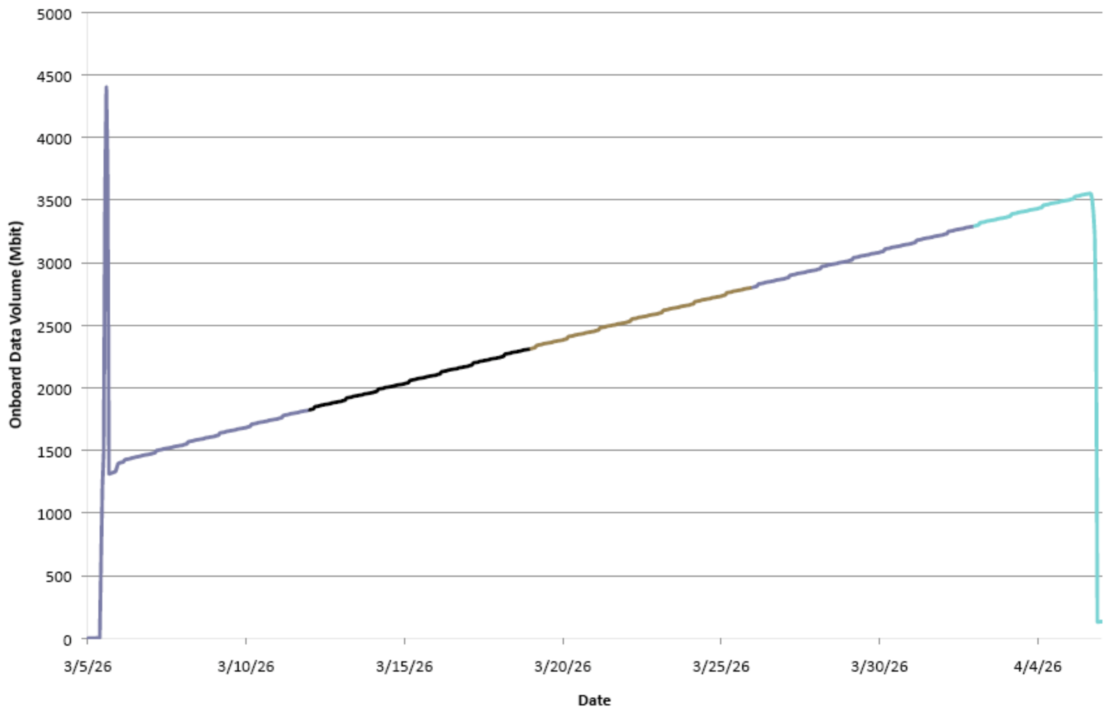


Figure 3-33. Floating Lander Onboard Data Volume by Time—Option 1

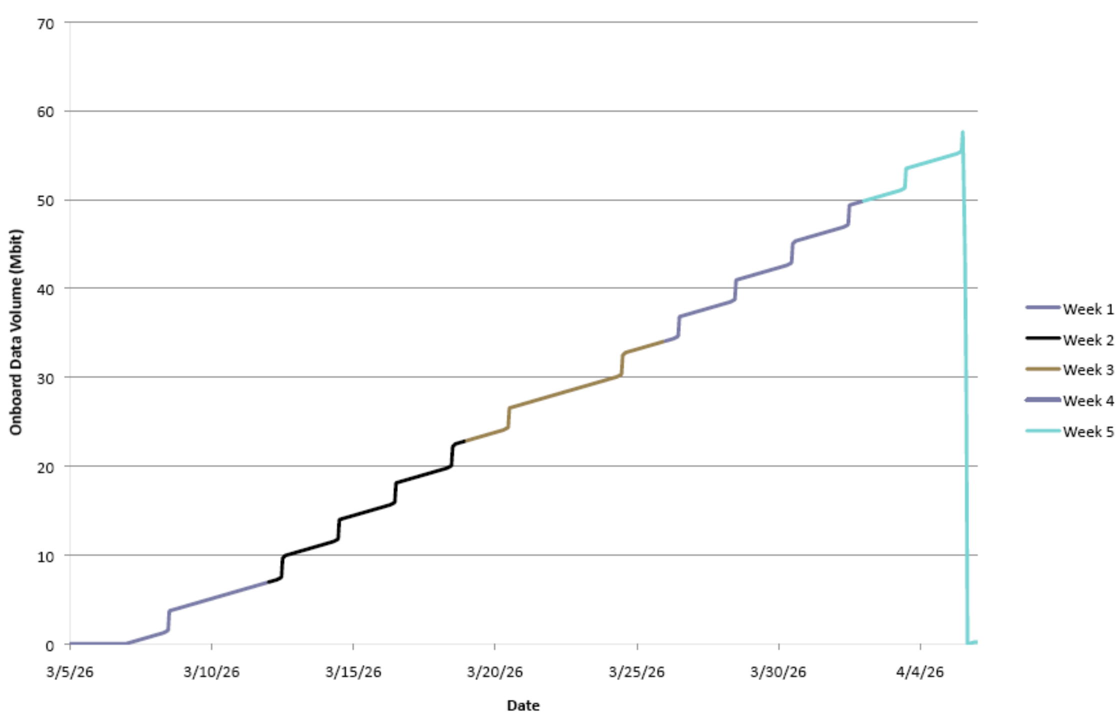


Figure 3-34. Submersible Onboard Data Volume by Time—Option 1

It should be noted that in Table 3-22, there is a column for telecommunications to the floating lander. The transfer of data from the submersible to the floating lander would begin as soon as the submersible starts to take data. While the two vehicles are connected, this communication would make use of a hardwired interface between the vehicles. In order to continue this data transfer after the separation of these two vehicles, a VHF link would be used for communication through the lake medium. However, this would only be a one-way transfer of data with no feedback of control information. It is not now known how long this link may be effective before the floating lander drifts out of range. For the purposes of this analysis, it was assumed that data would be transferred to the floating lander only through the end of day 2. After that time, no data would be transferred.

There would be one communications pass by the Flagship orbiter during EDL and for the first few hours of operation on the surface. The spike in onboard data volume shown in Figure 3-33 is an artifact of the early data collection by both the floating lander and the submersible, and the transfer of that data to the orbiter.

Without a return link from the floating lander to the submersible, the submersible would not know which data products sent to the floating lander were correctly received by the Flagship orbiter and forwarded to the orbiter and Earth. If the vehicles for this mission were to use the Delay Tolerant Networking (DTN) protocols for data return, then when the submersible is in contact with the orbiter at the end of the submerged portion of the mission, the orbiter would be able to determine which submersible data products have already been received and forwarded to Earth, and which would need to be retransmitted by the submersible. Otherwise, it would be necessary for the submersible to retransmit all data products that were earlier sent to the floating lander, thus wasting precious data volume capacity. The DTN protocols are expected to be state-of-the-practice well before the timeframe of this mission.

Figure 3-34 shows the cumulative onboard data volume for the submersible vehicle. As seen here, all of the data would be transferred to the floating lander early in the submersible mission. Once this transfer is complete, the data would collect onboard until the submersible surfaces and the orbiter is available for data relay after 32 days. At this time, all of the submersible data would be transferred to the orbiter before the data transfer from the floating lander is started.

It should also be noted that during the simulation, a small amount of data (132 Mbits) was left onboard the floating lander at the end of the second communications pass to the orbiter. In total, 82.3 Mbits were collected by the submersible and 6979.2 Mbits were collected by the floating lander.

Power Usage Simulations. The information presented in Tables 3-22 and 3-25 were used to create a simulation of the power that would be used by the major electrical loads in the floating lander over the course of the mission. The results of this simulation are shown in Figure 3-35. The floating lander would use a pair of ASRGs as a power source during the mission; these devices are capable of supplying the floating lander with up to 260 W of power. When the electrical load exceeds this value, then a set of rechargeable batteries would be used to make up the deficit in the floating lander’s energy balance. With a 2000 W-Hr battery in the floating lander, it would be possible to run the surface mission without going below the normal 60% depth of discharge limit for rechargeable batteries, as shown in Figure 3-36.

Similarly, it is possible to derive a simulation of the electrical loads in the submersible from the information in Table 3-22 and in Table 3-26. Assuming a primary battery of 12 KW-Hr in the submersible, a battery depth-of-discharge simulation was created for the submersible, as shown in Figure 3-37. This simulation shows that the mission could be performed while maintaining a depth of discharge of less than 80%, as required by JPL’s design rules.

Table 3-25. Floating Lander Power Calculations—Option 1

Electrical Load	Power Load CBE (W)	Uncertanty (%)	Conversion Efficiency (%)	Harness Losses (%)	Load, Fully Margined (W)
		30%		15%	
Descent GC-GC/MS	150	30%	100%	15%	224.25
High Res GC-GC/MS	150	30%	100%	15%	224.25
Surface MS	150	30%	100%	15%	224.25
Mass Spec Warm-Up	25	30%	100%	15%	37.38
		30%	100%	15%	0.00
Echo Sounder	5	30%	100%	15%	7.48
LPP Package	10	30%	100%	15%	14.95
LPP Warm-Up	17	30%	100%	15%	25.42
Turpidimeter		30%	100%	15%	0.00
Magnetometer	2	30%	100%	15%	2.99
Mast Mtd Instr	96.75	30%	100%	15%	144.64
Mast Mtd Instr Warm-Up	90	30%	100%	15%	134.55
DISR Package	11	30%	100%	15%	16.45
DISR Solar Aureole	11	30%	100%	15%	16.45
DISR Warm-Up	39	30%	100%	15%	58.31
Descent Camera (2)	13	30%	100%	15%	19.44
Descent Camera Warm-Up	8	30%	100%	15%	11.96
Surface Cameras (3)	13	30%	100%	15%	19.44
Surface Cameras Warm-Up	5	30%	100%	15%	7.48
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
CDS	54	30%	100%	15%	80.73
ACS	7.54	30%	100%	15%	11.27
Thermal	4	30%	100%	15%	5.98
Telecom (T+R)	75	30%	100%	15%	112.13
Telecom R	15	30%	100%	15%	22.43
Power		30%	100%	15%	0.00
		30%	100%	15%	0.00
Submersible		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00

Table 3-26. Submersible Power Calculations—Option 1

Electrical Load	Power Load CBE (W)	Uncertanty (%)	Conversion Efficiency (%)	Harness Losses (%)	Load, Fully Margined (W)
		30%		15%	
GC-GC/MS	150	30%	100%	15%	224.25
GC-GC/MS Warm-Up	25	30%	100%	15%	37.38
MS	100	30%	100%	15%	149.50
FTIR Spectrometer	10	30%	100%	15%	14.95
FTIR Spec Warm-Up	5	30%	100%	15%	7.48
		30%	100%	15%	0.00
LPP	10	30%	100%	15%	14.95
		30%	100%	15%	0.00
Echo Sounder	5	30%	100%	15%	7.48
		30%	100%	15%	0.00
		30%	100%	15%	0.00
Turpidimeter	10	30%	100%	15%	14.95
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
CDS Instr On	9	30%	100%	15%	13.46
CDS Instr Off	2	30%	100%	15%	2.99
Thermal	1	30%	100%	15%	1.50
Telecom UHF	20	30%	100%	15%	29.90
Telecom to Orb	75	30%	100%	15%	112.13
Telecom R only	15	30%	100%	15%	22.43
		30%	100%	15%	0.00
Submersible		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00

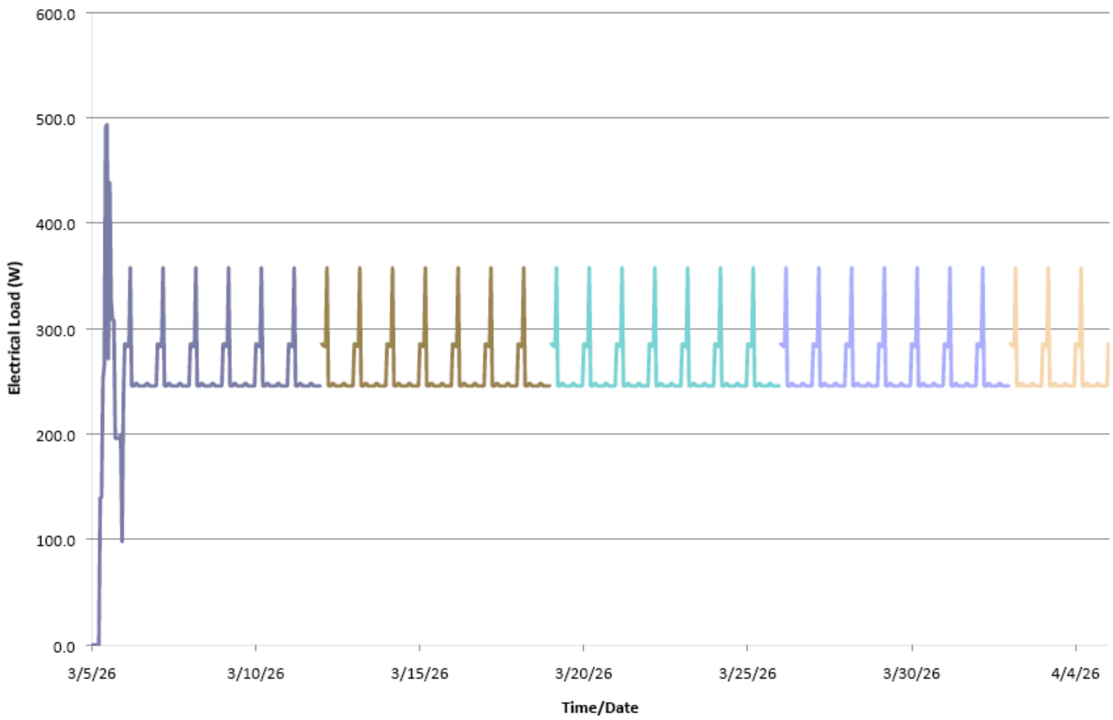


Figure 3-35. Floating Lander Electrical Load by Time—Option 1

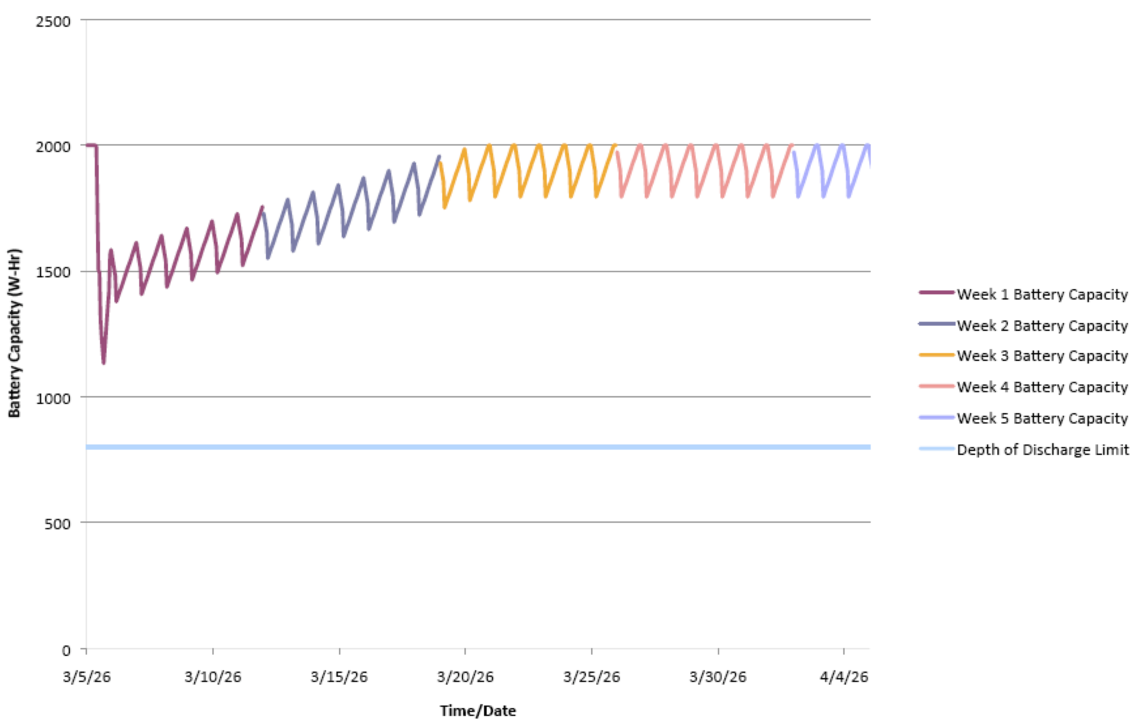


Figure 3-36. Floating Lander Battery State of Charge by Time—Option 1

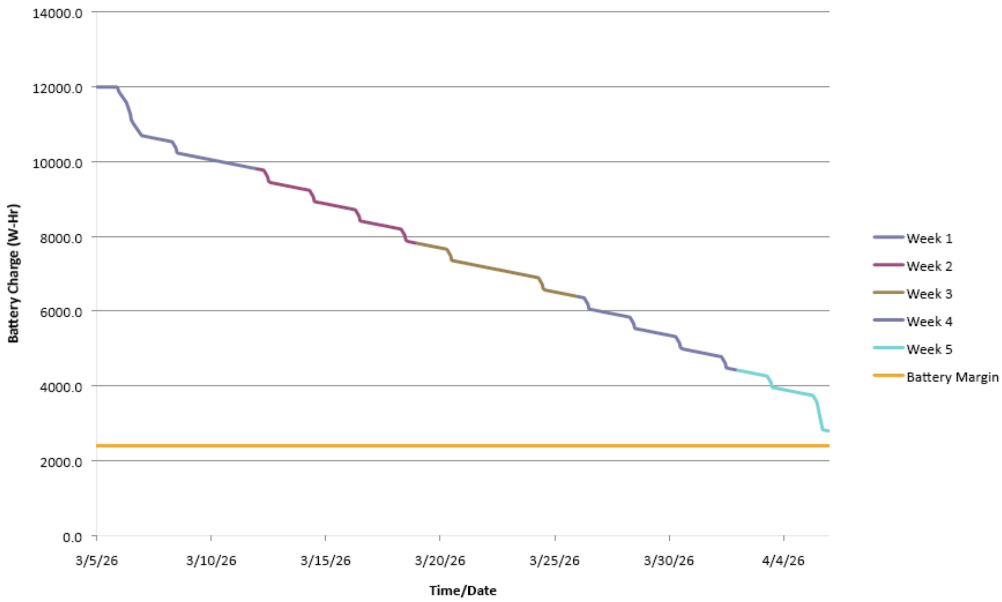


Figure 3-37. Submersible Battery State of Charge by Time—Option 1

Option 2: New Frontiers Floating Lander with Direct-to-Earth Communications

The timeline for this option is shown in Table 3-27. This option would include a floating lander as the landed element. The table indicates when each instrument would be on and taking data. It also indicates how many observations would be taken during the particular period (for observation-based instruments) or what fraction of the time the instrument would be on for the time period (for data rate–based instruments).

Data Volume Simulations. The telecommunications column in Table 3-27 indicates when data could be transferred from the floating lander to Earth by using the floating lander's DTE communications link at X-band. Communications to Earth are only available for a limited amount of time, once each during the 16-day orbits of Titan around Saturn. These communications windows are only open for a few days in each Titan orbit. Furthermore, because the selected landing site at Kraken Mare is at a high latitude in Titan's northern hemisphere, and the available launch window for a New Frontiers mission would be in the early 2020s, the length of these windows will be getting progressively shorter. Figure 3-38 shows the length of these windows over time. A mission landing date of March 5, 2026 was chosen for this simulation. As can be seen in Figure 3-38, these communications windows will be getting progressively shorter at later dates, disappearing entirely by mid-2029. This situation could be greatly improved by landing in a Southern hemisphere lake. The team investigated an alternate landing site at Ontario Lacus, but this lake was determined to be too risky given the present state of knowledge.

The information presented in Table 3-27 was used to calculate a simulation of the amount of data generated over time by the instrument suite with data volumes or data rates indicated in Table 3-28. Results of these simulations for the DTE floating lander are shown in Figure 3-39.

It should also be noted that a small amount of data (2.3 Mbits) was left onboard the floating lander at the end of the simulation. In total, the floating lander collected 495.8 Mbits of data; this small residual could be easily returned to Earth by continuing the downlink simulation for one more hour. However, as the length of the communications windows deteriorates over time, it would be difficult and finally impossible to return a data volume in the 450 to 500 Mbit range within three or four communications windows.

Table 3-27. Timeline—Option 2

Event	Time (Days)	Time (Hrs)	Tele Comm	Floater: Lo res GC-GC MS	LPP	Echo	Turbid	Mast wind	Descent cam	Surf cam
	D1	0								
		1	DTE							
		2								
		3								
		4								
		5								
		6								
		7								
		8								
		9								
start aerial descent		10							5	
		11								
splashdown		12			Continuous	417 over period		600 per hour		24
		13								
		14								
		15								
		16								
		17								
		18								
		19								
		20								
		21								
		22								
		23								
	D2			1						1
	D3									1
	D4			1						1
	D5									1
	D6			1						1
	D7									1
	D8			1						1
	D9									1
	D10			1						1
	D11									1
	D12			1						1
	D13									1
	D14			1						1
	D15									1
	D16			1						1
	D17									1
	D18			1						1
	D19									1
	D20			1						1
	D21									1
	D22			1						1
	D23									1
	D24			1						1
	D25									1
	D26			1						1
	D27									1
	D28			1						1
	D29									1
	D30			1						1
	D31									1
	D32	0		1						1
		1								
		2								
		3								
		4								
		5								
		6								
		7								
		8								
		9								
		10								
		11								
		12								
		13								
		14								
		15								
		16								
		17								
		18								
		19								
		20								
		21								
		22								
		23								
	D33									
	D34									

Table 3-28. Telemetry Calculations—Option 2

Instrument	Data Rate (Kbps) or Observation Size (Kbits)	Observation or Constant Rate	Instrument Hourly or Observation Data Volume (Mbits)	Formatting Overhead (Mbits)	Hourly or Observation Data Volume w/Overhead (Mbits)	Margin Data Volume (Mbits)	Hourly or Observation Data Volume w/Margin (Mbits)
				Overhead 7%		Margin 0%	
Low Res GC-GC MS	2016.0	Obs	2.016	0.1	2.2	0.0	2.2
GC-GC MS Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.0
			0.000	0.0	0.0	0.0	0.0
LPP Instruments	0.026	Obs	0.000	0.0	0.0	0.0	0.000
LPP Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
			0.000	0.0	0.0	0.0	0.000
Echo Sounder	0.016		0.000	0.0	0.0	0.0	0.000
			0.000	0.0	0.0	0.0	0.000
Turpidimeter			0.000	0.0	0.0	0.0	0.000
			0.000	0.0	0.0	0.0	0.000
Mast Instruments	0.191	Obs	0.000	0.0	0.0	0.0	0.000
Mast Instr Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
			0.000	0.0	0.0	0.0	0.000
Descent Cameras	6292.0	Obs	6.292	0.4	6.7	0.0	6.732
Descent Camera Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
			0.000	0.0	0.0	0.0	0.000
Surface Cameras	3146.0	Obs	3.146	0.2	3.4	0.0	3.366
Surface Camera Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031
			0.000	0.0	0.0	0.0	0.000
			0.000	0.0	0.0	0.0	0.0
			0.000	0.0	0.0	0.0	0.0
			0.000	0.0	0.0	0.0	0.0
Engineering Data High	1.0	Rate	3.600	0.3	3.9	0.0	3.9
Engineering Data Low	0.04	Rate	0.144	0.0	0.2	0.0	0.2

Power Usage Simulations. The information presented in Tables 3-27 and 3-29 were used to create a simulation of the power used by the major electrical loads in the floating lander over the course of the mission. The results of this simulation are shown in Figure 3-40. The floating lander would use a pair of ASRGs as a power source during the mission; these devices would be capable of supplying the floating lander with up to 260 W of power. When the electrical load exceeds this value, then a set of rechargeable batteries would be used to make up the shortfall in the floating lander's energy balance. With a 6500 W-Hr battery in the floating lander, it would be possible to run the surface mission without going below the normal 60% depth of discharge limit for rechargeable batteries, as shown in Figure 3-41.

Table 3-29. Power Calculations—Option 2

Electrical Load	Power Load CBE (W)	Uncertanty (%)	Conversion Efficiency (%)	EPS Losses (%)	Load, Fully Margined (W)
		30%		15%	
Low Res GC-GC MS	150	30%	100%	15%	224.25
GC-GC MS Warm-Up	25	30%	100%	15%	37.38
		30%	100%	15%	0.00
LPP Instruments	10	30%	100%	15%	14.95
LPP Warm-Up	17	30%	100%	15%	25.42
		30%	100%	15%	0.00
Echo Sounder	5	30%	100%	15%	7.48
		30%	100%	15%	0.00
Turpidimeter		30%	100%	15%	0.00
		30%	100%	15%	0.00
Mast Instruments	36.75	30%	100%	15%	54.94
Mast Instr Warm-Up	90	30%	100%	15%	134.55
		30%	100%	15%	0.00
Descent Cameras	11	30%	100%	15%	16.45
Descent Camera Warm-Up	8	30%	100%	15%	11.96
		30%	100%	15%	0.00
Surface Cameras	13	30%	100%	15%	19.44
Surface Camera Warm-Up	5	30%	100%	15%	7.48
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
CDS	54	30%	100%	15%	80.73
ACS	16	30%	100%	15%	23.92
Thermal	4	30%	100%	15%	5.98
Telecom (T+R)	75	30%	100%	15%	112.13
Telecom R	15	30%	100%	15%	22.43
Power		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00

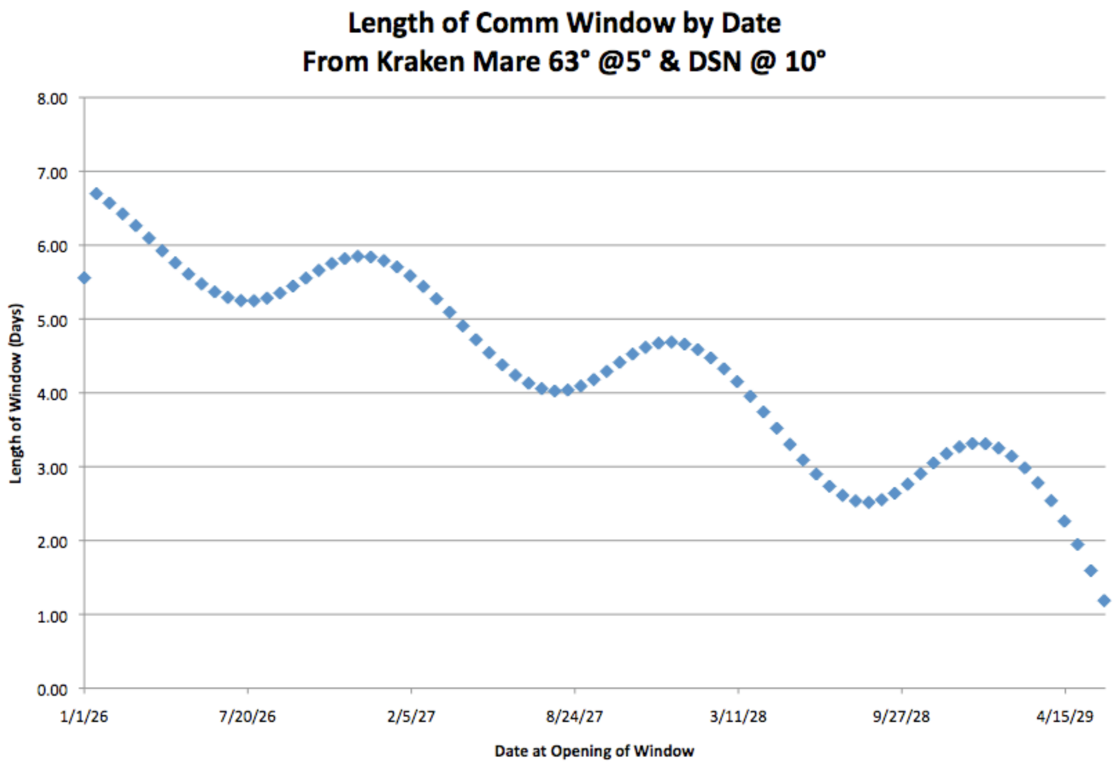


Figure 3-38. Length of DTE Communications Windows

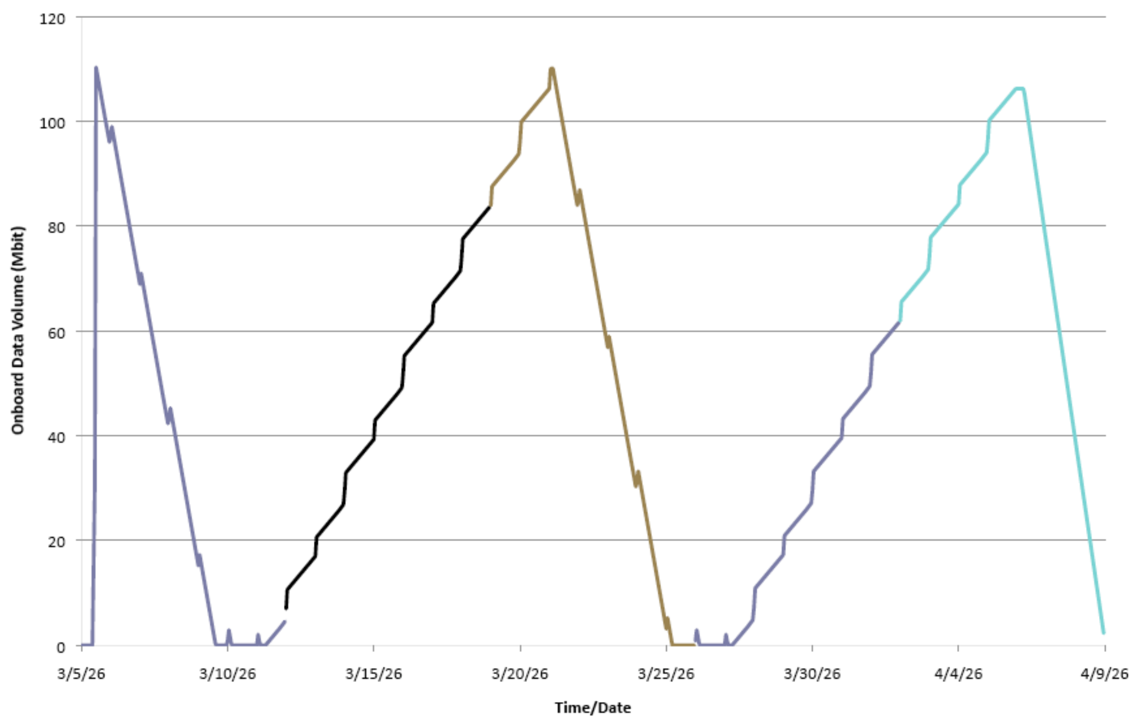


Figure 3-39. Floating Lander Onboard Data Volume—Option 2

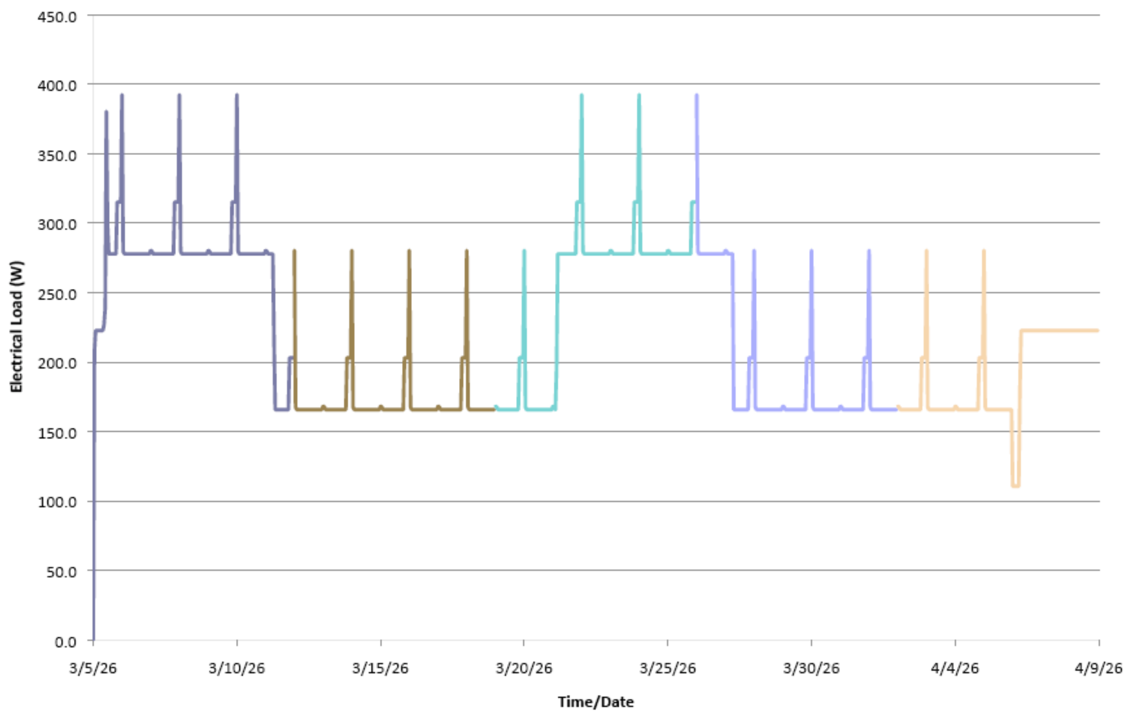


Figure 3-40. Floating Lander Electrical Load—Option 2

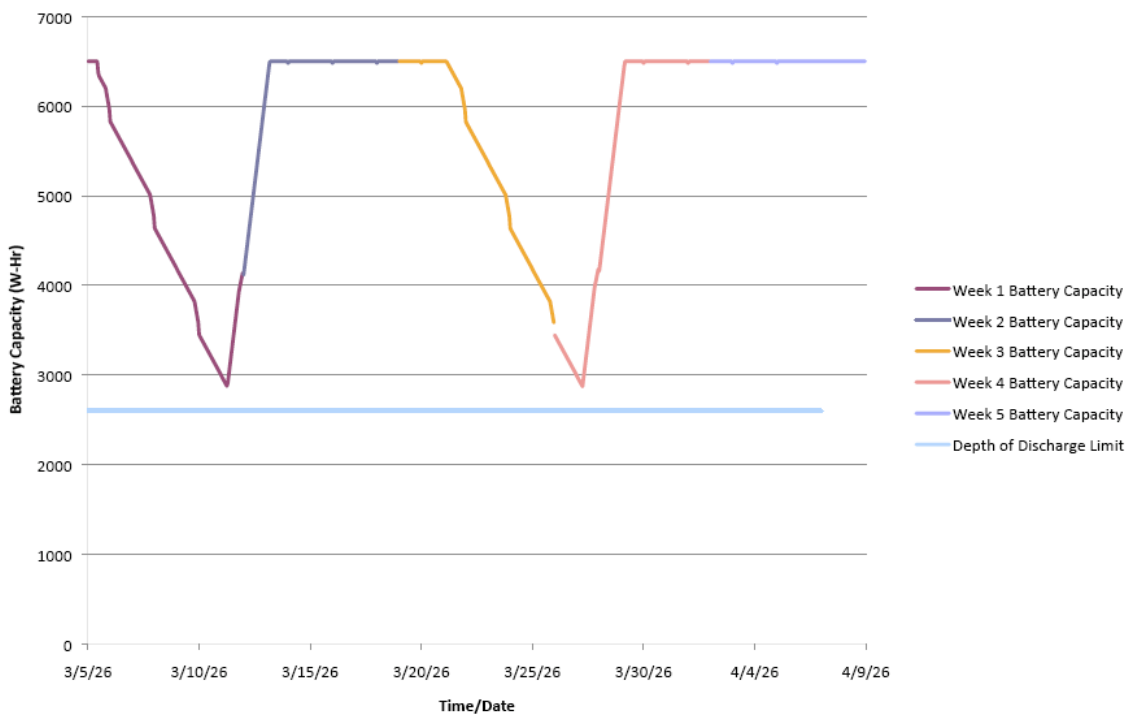


Figure 3-41. Floating Lander Battery State of Charge—Option 2

Option 3: New Frontiers Submersible with Relay to a Smart Cruise Stage

The timeline for this option is shown in Table 3-30. This option would include a submersible as the landed element and a "smart" cruise stage that would also be used to relay the submersible data to Earth. This table indicates when each instrument would be on and taking data. It also shows how many observations would be taken during the particular period (for observation-based instruments) or what fraction of the time the instrument would be on for the time period (for data rate–based instruments).

Data Volume Simulations. The telecommunications column in Table 3-30 indicates when data could be transferred from the submersible to the cruise/relay vehicle to be forwarded to Earth on a store-and-forward basis. Communications to Earth would only be available through the cruise/relay vehicle when this vehicle would be visible to the submersible on the surface of the lake and the cruise/relay would be at a short range. The cruise/relay vehicle could receive approximately 3150 Mbit of data from the submersible.

The information presented in Table 3-30 was used to calculate a simulation of the amount of data generated over time by the instrument suite with data volumes or data rates indicated in Table 3-31. Results of these simulations for the DTE floating lander are shown in Figure 3-42. In total, the submersible would collect 1595.7 Mbits of data during the mission, so the cruise/relay vehicle could easily receive and store the full set of submersible data.

Power Usage Simulations. The information presented in Tables 3-30 and 3-32 was used to create a simulation of the power used by the major electrical loads in the submersible over the course of the mission. The battery depth-of-discharge simulation, shown in Figure 3-43, assumed the use of a 6.5 KW-Hr primary battery in the submersible. This simulation shows that the mission could be performed while maintaining a depth of discharge of less than 80%, as required by JPL design rules.

Table 3-30. Timeline—Option 3

Event	Time (Days)	Time (Hrs)	Tele Comm Relay	Sub H/Lo res GC-GC MS	FTIR	LPP	Descent cam
	D1	0					
		1					
		2					
		3					
		4					
		5					
		6					
		7					
		8					
		9					
start aerial descent		10		12 @ 15 Mb			5
		11		12 @ 15 Mb			
splashdown		12		1 Gbit			
		13		2 @ 2016kb			
		14		2 @ 2016kb			
		15		2 @ 2016kb			
		16		2 @ 2016kb			
		17		2 @ 2016kb			
start sub descent		18			204	2000	
		19			204	2000	
sub reaches bottom		20				1 obs each hour	
		21		2 @ 2016kb			
		22		2 @ 2016kb			
		23		2 @ 2016kb			
	D2	0		2 @ 2016kb			
		1		2 @ 2016kb			
start sub ascent		2					
		3					
sub reaches surface		4					
		5					
		6					
		7					
		8					
		9					
		10					
		11					
		12					
		13					
		14					
		15					
		16					
		17					
		18					
		19					
		20					
		21					
		22					
		23					
	D3	0					
		1					
		2					
		3					
		4					
		5					
		6					
		7					
		8					
		9					
		10					
		11					
		12					

Table 3-31. Telemetry Calculations—Option 3

Instrument	Data Rate (Kbps) or Observation Size (Kbits)	Observation or Constant Rate	Instrument Hourly or Observation Data Volume (Mbits)	Formatting Overhead (Mbits)	Hourly or Observation Data Volume w/Overhead (Mbits)	Margin Data Volume (Mbits)	Hourly or Observation Data Volume w/Margin (Mbits)	Data Volume Compression Factor	Instrument Compressed Data Volume per Hour or Observation (Mbits)
				Overhead 7%		Margin 0%			
High Res GC-GC MS	1000000.0	Obs	1000.000	70.0	1070.0	0.0	1070.0	1	1,070.0000
Low Res GC-GC MS	2016.0	Obs	2.016	0.1	2.2	0.0	2.2	1	2.1571
Atmosphere GC-GC MS	15000.0	Obs	15.000	1.1	16.1	0.0	16.1	1	16.0500
GC-GC MS Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
FTIR Spectrometer	144.0	Obs	0.144	0.0	0.2	0.0	0.154	1	0.1541
FTIR Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
LPP Instrument	0.026	Obs	0.000	0.0	0.0	0.0	0.000	1	0.0000
LPP Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
Descent Cameras	6292.0	Obs	6.292	0.4	6.7	0.0	6.732	1	6.7324
Descent Camera Warm-	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
Engineering Data	0.5	Rate	1.800	0.1	1.9	0.0	1.9	1	1.9260
Engineering Data	0.1	Rate	0.180	0.0	0.2	0.0	0.2	1	0.1926

Table 3-32. Power Calculations—Option 3

Electrical Load	Power Load CBE (W)	Uncertanty (%)	Conversion Efficiency (%)	Harness Losses (%)	Load, Fully Margined (W)
		30%		15%	
High Res GC-GC MS	150	30%	100%	15%	224.25
Low Res GC-GC MS	150	30%	100%	15%	224.25
Atmosphere GC-GC MS	100	30%	100%	15%	149.50
GC-GC MS Warm-Up	25	30%	100%	15%	37.38
		30%	100%	15%	0.00
FTIR Spectrometer	10	30%	100%	15%	14.95
FTIR Warm-Up	5	30%	100%	15%	7.48
		30%	100%	15%	0.00
LPP Instrument	10	30%	100%	15%	14.95
LPP Warm-Up	17	30%	100%	15%	25.42
		30%	100%	15%	0.00
Descent Cameras	11	30%	100%	15%	16.45
Descent Camera Warm-Up	8	30%	100%	15%	11.96
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
CDS	9	30%	100%	15%	13.46
ACS	0	30%	100%	15%	0.00
Thermal	1	30%	100%	15%	1.50
Telecom (T+R)	75	30%	100%	15%	112.13
Telecom R	15	30%	100%	15%	22.43
Power		30%	100%	15%	0.00
		30%	100%	15%	0.00
Submersible		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00

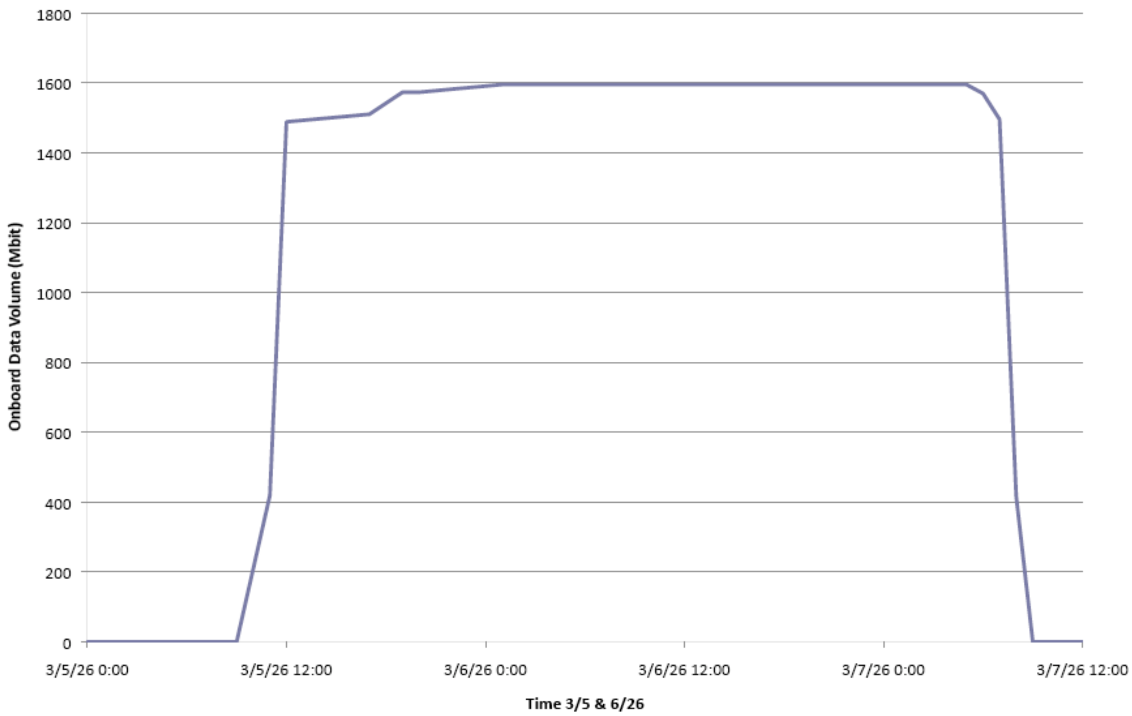


Figure 3-42. Submersible Onboard Data Volume—Option 3

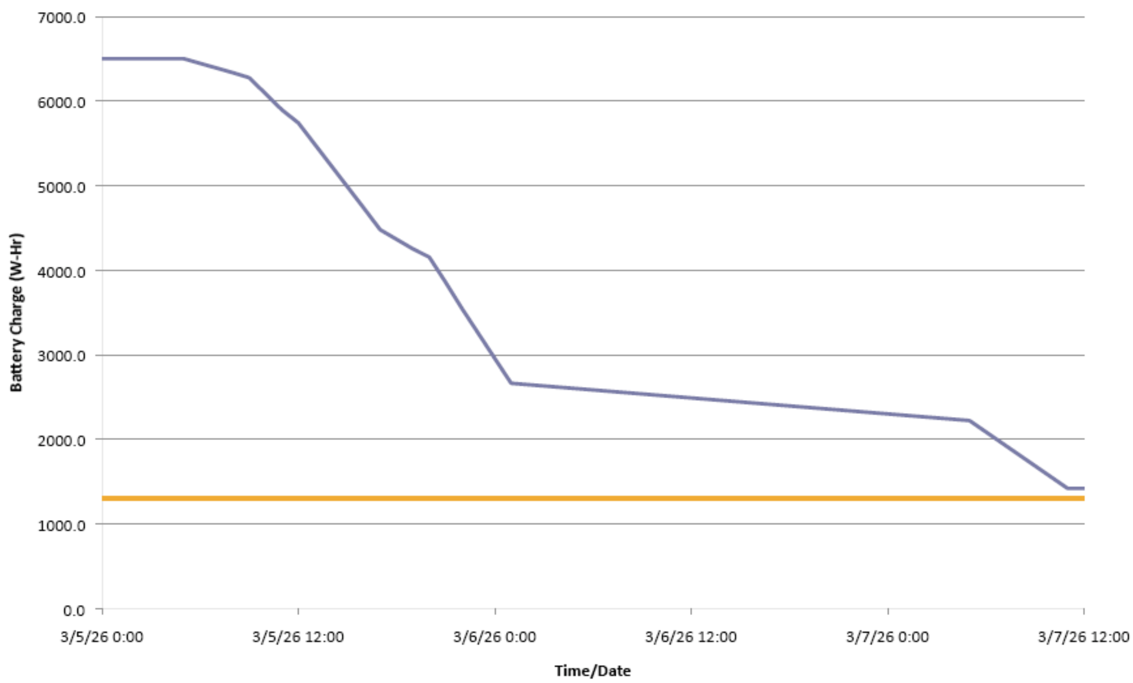


Figure 3-43. Battery State of Charge—Option 3

Option 4: New Frontiers Floating Lander with Relay to a Smart Cruise Stage

The timeline for this option is shown in Table 3-33. This option includes a floating lander as the landed element. This table indicates when each instrument would be on and taking data. It also indicates how many observations would be taken during the particular period (for observation based instruments) or what fraction of the time the instrument would be on for the time period (for data rate–based instruments).

Data Volume Simulations. The telecommunications column in Table 3-33 indicates when data could be transferred from the floating lander to the cruise/relay vehicle to be forwarded to Earth on a store-and-forward basis. Communications to the Earth would only be available through the cruise/relay vehicle when this vehicle would be visible to the floating lander and the cruise/relay would be at a short range. The cruise/relay vehicle could receive approximately 3010.6 Mbit of data from the floating lander.

The information presented in Table 3-33 was used to calculate a simulation of the amount of data generated over time by the instrument suite with data volumes or data rates indicated in Table 3-34. Results of these simulations for the DTE floating lander are shown in Figure 3-44. In total, the floating lander would collect 1529.0 Mbits of data during the mission, so the cruise/relay vehicle can easily receive and store the full set of the floating lander data.

Power Usage Simulations. The information in Tables 3-33 and 3-35 was used to create a simulation of the power used by the major electrical loads in the floating lander over the course of the mission. The battery depth-of-discharge simulation, as shown in Figure 3-45, assumed the use of a 5.0 KW-Hr primary battery in the floating lander. This simulation shows that the mission could be performed while maintaining a depth of discharge of less than 80%, as required by the JPL design rules.

Table 3-33. Timeline—Option 4

				Floater				
Event	Time (Days)	Time (Hrs)	Tele Comm Relay	Hi res GC-GC MS	LPP	Descent cam	Air Pressure Sensor	Air Temp Sensor
turn on hi res MS								
	D1	0						
		1						
		2						
		3						
		4						
		5						
		6						
		7						
		8						
		9						
start aerial descent		10		12 @ 15 Mb		5		
		11		12 @ 15 Mb				
splashdown		12		1 Gbit	Continuous			600
		13		2 @ 2016kb				600
		14		2 @ 2016kb				600
		15		2 @ 2016kb				600
		16		2 @ 2016kb				600
		17		2 @ 2016kb				600
		18		2 @ 2016kb				600
		19		2 @ 2016kb				600
		20		2 @ 2016kb				600
		21		2 @ 2016kb				600
		22						
		23						

Table 3-34. Telemetry Calculations—Option 4

Instrument	Data Rate (Kbps) or Observation Size (Kbits)	Observation or Constant Rate	Instrument Hourly or Observation Data Volume (Mbits)	Formatting Overhead (Mbits)	Hourly or Observation Data Volume w/Overhead (Mbits)	Margin Data Volume (Mbits)	Hourly or Observation Data Volume w/Margin (Mbits)	Data Volume Compression Factor	Instrument Compressed Data Volume per Hour or Observation (Mbits)
				Overhead 7%		Margin 0%			
High Res GC-GC MS	1000000.0	Obs	1000.000	70.0	1070.0	0.0	1070.0	1	1,070.0000
Low Res GC-GC MS	2016.0	Obs	2.016	0.1	2.2	0.0	2.2	1	2.1571
Atmosphere GC-GC MS	15000.0	Obs	15.000	1.1	16.1	0.0	16.1	1	16.0500
GC-GC MS Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
Temp/Pressure Sensors	0.028	Obs	0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
LPP Instrument	0.026	Rate	0.094	0.0	0.1	0.0	0.100	1	0.1002
LPP Warm-Up	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
Descent Cameras	6292.0	Obs	6.292	0.4	6.7	0.0	6.732	1	6.7324
Descent Camera Warm-	0.008	Rate	0.029	0.0	0.0	0.0	0.031	1	0.0308
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.000	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
			0.000	0.0	0.0	0.0	0.0	1	0.0000
Engineering Data	0.5	Rate	1.800	0.1	1.9	0.0	1.9	1	1.9260
Engineering Data	0.1	Rate	0.180	0.0	0.2	0.0	0.2	1	0.1926

Table 3-35. Power Calculations—Option 4

Electrical Load	Power Load CBE (W)	Uncertanty (%)	Conversion Efficiency (%)	Harness Losses (%)	Load, Fully Margined (W)
		30%		15%	
High Res GC-GC MS	150	30%	100%	15%	224.25
Low Res GC-GC MS	150	30%	100%	15%	224.25
Atmosphere GC-GC MS	100	30%	100%	15%	149.50
GC-GC MS Warm-Up	25	30%	100%	15%	37.38
		30%	100%	15%	0.00
Temp/Pressure Sensors	1.25	30%	100%	15%	1.87
		30%	100%	15%	0.00
		30%	100%	15%	0.00
LPP Instrument	10	30%	100%	15%	14.95
LPP Warm-Up	17	30%	100%	15%	25.42
		30%	100%	15%	0.00
Descent Cameras	11	30%	100%	15%	16.45
Descent Camera Warm-Up	8	30%	100%	15%	11.96
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
CDS	9	30%	100%	15%	13.46
ACS	0	30%	100%	15%	0.00
Thermal	1	30%	100%	15%	1.50
Telecom (T+R)	75	30%	100%	15%	112.13
Telecom R	15	30%	100%	15%	22.43
Power		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00
		30%	100%	15%	0.00

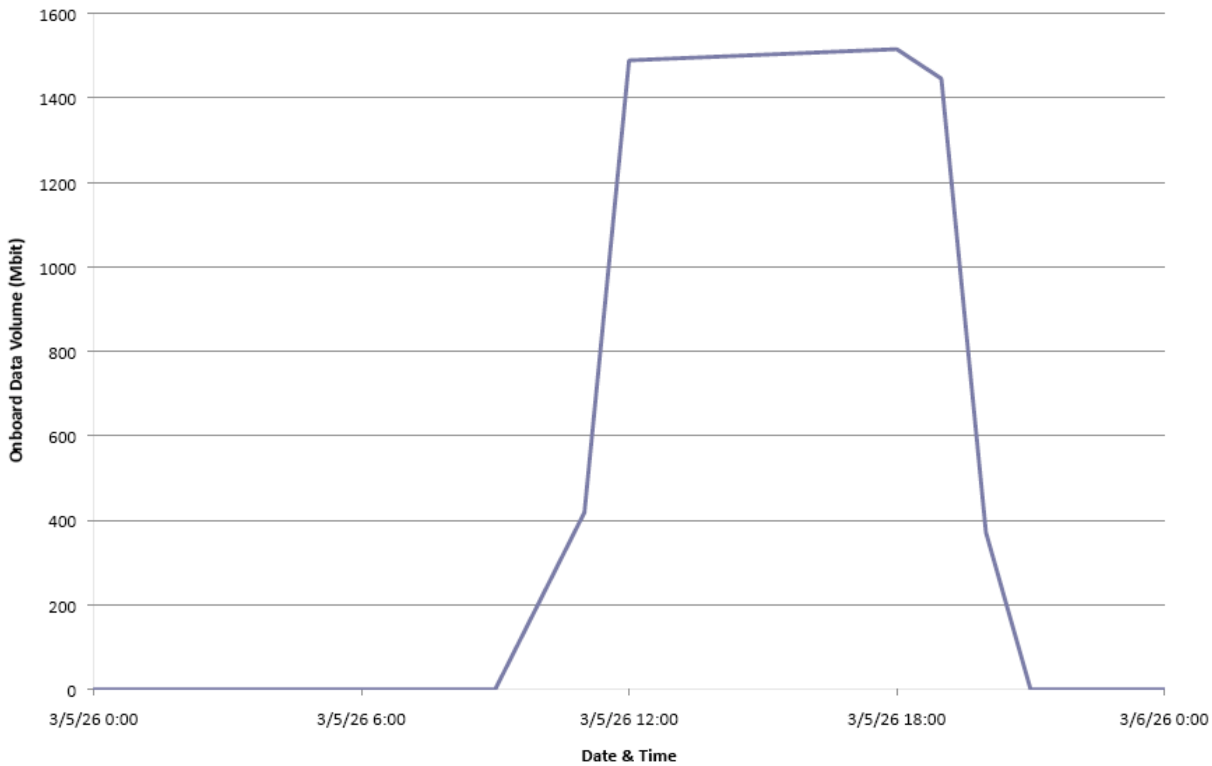


Figure 3-44. Floating Lander Onboard Data Volume—Option 4

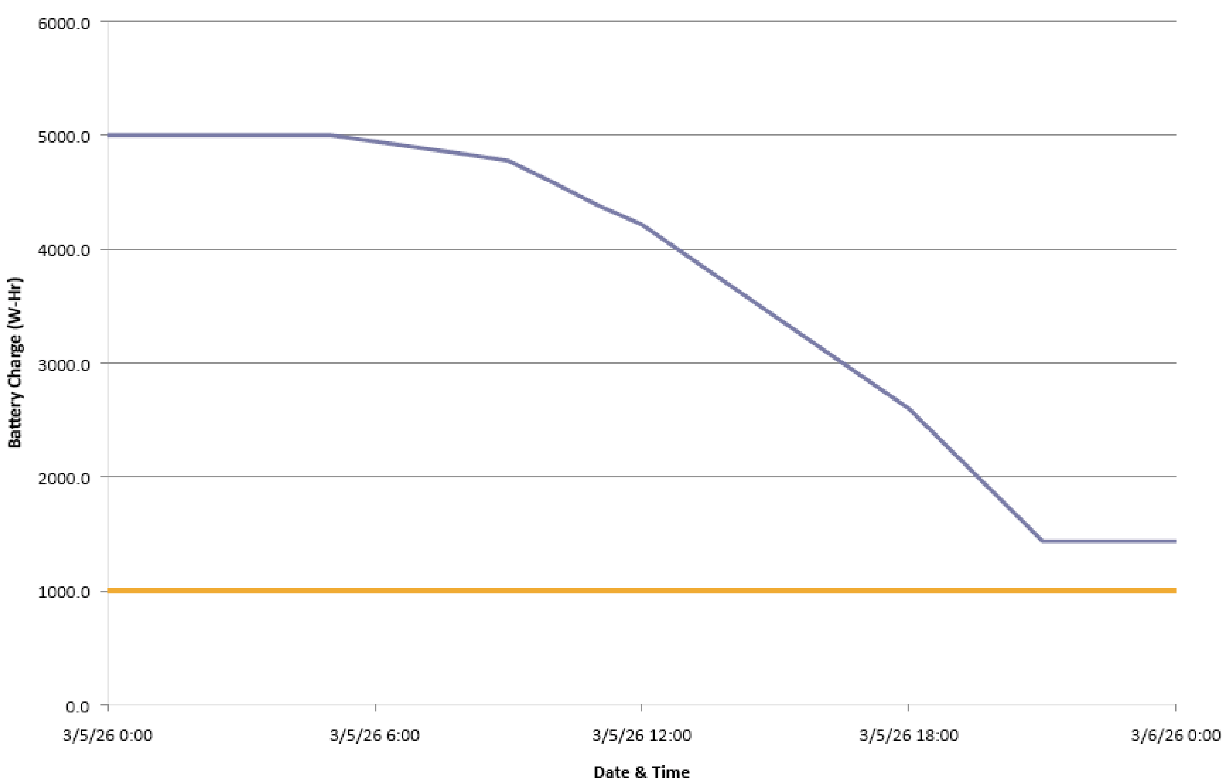


Figure 3-45. Floating Lander Battery State of Charge—Option 4

Planetary Protection

In accordance with NPR 8020.12C, the Titan Lake Probe mission is expected to be a Planetary Protection Category II mission. Accordingly, the Titan Lake Probe project would demonstrate that its mission meets the Category II planetary protection requirements per NPR 8020.12C, Appendix A.2. The planetary protection category of the mission would be formally established by the NASA planetary protection officer (PPO) in response to a written request from the Titan Lake Probe project manager, submitted by the end of Phase A.

The Titan Lake Probe project would prepare all planetary protection documents and hold all reviews as required by the NASA PPO. The project plans to demonstrate compliance with the non-impact requirements for Mars and Enceladus by a combination of trajectory biasing and analyses performed by the navigation team.[1] Compliance with the probability of biological contamination of Titan requirement would be demonstrated by analysis. An entry heating and break-up analysis would be performed, similar to the analyses performed for past Mars missions (i.e., MRO and MSL), to determine the level of contamination in the event of an uncontrolled Titan entry. The Titan Lake Probe team would also calculate the probability of creating a transient "special region"[2] in the event of an uncontrolled entry. A heat flow analysis of the perennial heat source(s) would be performed for the nominal end of the mission to determine if it is possible for the final resting point(s) of any spacecraft hardware containing a perennial heat source to melt water ice. If the probability of contamination exceeds the requirement, then the spacecraft would be cleaned / microbially reduced as needed to meet the requirement (note: this is not included in the cost estimate). The results of all of these analyses would be documented in the planetary protection pre-launch report. The navigation team would also identify the location of the landing point on Titan. This location would be reported in the planetary protection end-of-mission report.

Risk List

The study identified eight moderate and two low risks as significant at the system level. All risks are related to operations, and most are common for any outer planets mission with a long cruise stage and the use of nuclear power. While instrument risks are not specifically identified in the risk list (other than cryogenic sample acquisition), it should be noted that a significant amount of instrument related technology development critical to the success of this mission concept has been identified in section 4 of this report. This risk assessment assumes that those technologies will have been developed in time for use in this mission and does not account for the risk of their development not occurring successfully. Figure 3-46 provides a summary of the risks on a 5 x 5 matrix. More detailed definitions for mission and implementation risks are described in Table 3-36.

Due to the early stage of the design and the limited study time, identification of risk mitigations was only feasible for a small number of risks. Five of the risks cut across all options. Three risks were unique to Option 2 and two risks impacted Options 3 and 4 only.

Tables 3-37 and 3-38 expand on the details of each risk element and provide mitigated scores where applicable.

---

[1] For Option 1: The majority of this work is to be performed as part of the carrier mission

[2] "Special region" is a localized environment where conditions (temperature, water activity) might occur that are conducive to replication of any terrestrial organisms carried on the spacecraft.

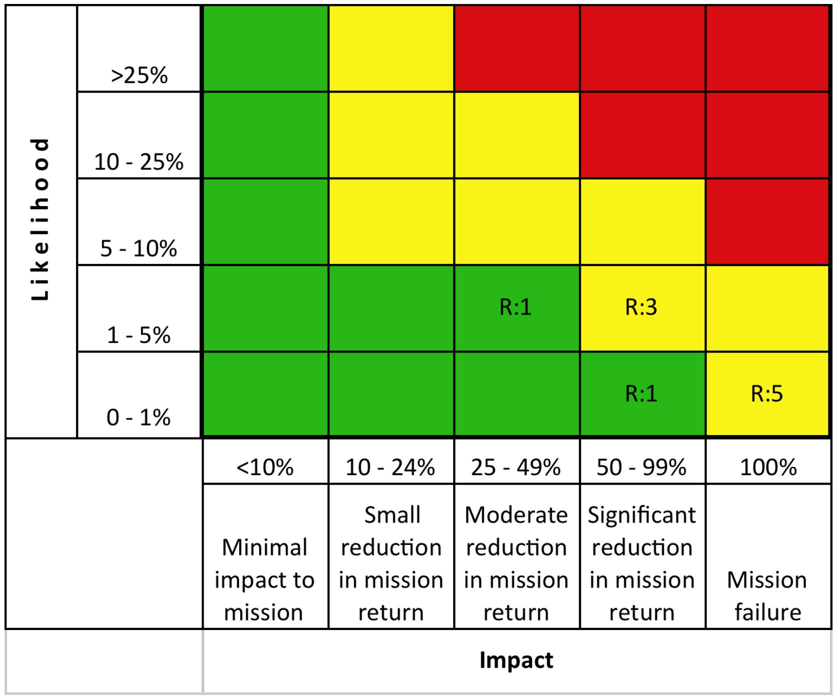


Figure 3-46. Risk Matrix

Table 3-36. Risk Level Definitions

Levels	Mission Risk		Implementation Risk	
	Impact	**Likelihood of Occurrence**	**Impact**	**Likelihood of Occurrence**
5	Mission failure	Very high, >25%	Consequence or occurrence is not repairable without engineering (would require >100% of margin)	Very high, ~70%
4	Significant reduction in mission return (~25% of mission return still available)	High, ~25%	All engineering resources will be consumed (100% of margin consumed)	High, ~50%
3	Moderate reduction in mission return (~50% of mission return still available)	Moderate, ~10%	Significant consumption of engineering resources (~50% of margin consumed)	Moderate, ~30%
2	Small reduction in mission return (~80% of mission return still available)	Low, ~5%	Small consumption of engineering resources (~10% of margin consumed)	Low, ~10%
1	Minimal (or no) impact to mission (~95% of mission return still available)	Very low, ~1%	Minimal consumption of engineering resources (~1% of margin consumed)	Very low, ~1%

Table 3-37. Detailed Risk Analysis of All Mission Options

Risk	Level	Description	Impact	Likelihood	Mitigation	Mitigated Impact	Mitigated Likelihood
All Options							
Gyro degradation due to radiation	M	Because power is limited, the baseline would include LN-200S gyros, which require 12 Watts, compared to 34 Watts or more for higher performance gyros. LN-200S gyros are rad soft; there have been reliability concerns as well. For this mission, ASRGs would provide power; therefore, there may be a perception that the gyros would be exposed to a high-radiation dose.	4	2	Shielding and Redundancy	–	–
Plutonium availability	M	Issues have arisen with the supply of plutonium from current suppliers (e.g., Russia). This raises concerns that a sufficient amount of Pu would not be available to meet the demand, which could impact cost and/or schedule.	5	1	–	–	–
ASRG reliability	M	ASRGs have not flown yet and have been lifetime tested on the ground for only a limited number of years; thus, operating characteristics and reliability are unknown. NASA Decadal Survey guidelines specify that the ASRGs would have a 17-year lifetime from beginning of manufacture. This implies a MTTF of at least 10 years for 95% reliability.	5	1	–	–	–
Possibility could miss the lake due to ballistic entry	M	While the likelihood is low, a ballistic entry does not allow any possibility of correction during EDL.	5	1	–	–	–
Cryogenic sample acquisition not well understood	L	While many aspects are similar to surface sampling methods on Mars, sampling in a liquid environment has not been done before at JPL or NASA.	3	2	–	3	1

Table 3-38. Detailed Risk Analysis of Individual Mission Options

Risk	Level	Description	Impact	Likelihood	Mitigation	Mitigated Impact	Mitigated Likelihood
Option 2 Only							
Sun sensors not adequate (Option 2)	M	Solar intensity at Titan is roughly 100 times less than at Earth. Due to atmospheric absorption, solar intensity at the surface of Titan may be reduced by another factor of 10 or more, compared with intensity in orbit. Sun sensors on the Option 2 floating lander may not have enough signal to accurately measure sun direction. This increases the risk of not finding the earth for telecom to point the HGA.	4	2	Alternate Pointing Architecture	1	1
HGA pointing (Option 2)	M	Uplink from Earth to a lander floating on a lake may cause loss of signal or inability to link at all.	5	1	–	–	–
Long mission impacts on component performance (Option 2)	L	If a mission is longer than five years, component reliability starts to become an issue. Cassini started to exhibit component failure after seven years. Since the mission is approximately six years, the likelihood is low, but impact could be total loss of mission.	4	1	–	–	–
Options 3 and 4 Only							
Release failure (Options 3 and 4)	M	There is always some potential for release failure. A nine-year cruise before release of the submersible / floating lander increases the likelihood.	5	1	–	–	–
Long mission impacts on component performance (Options 3 and 4)	L	If a mission is longer than five years, component reliability starts to become an issue. Cassini started to exhibit component failure after seven years. Since the mission is approximately nine years, the likelihood is higher than Option 2 (assuming 1–5%) but impact could be total loss of mission.	4	2	–	–	–

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

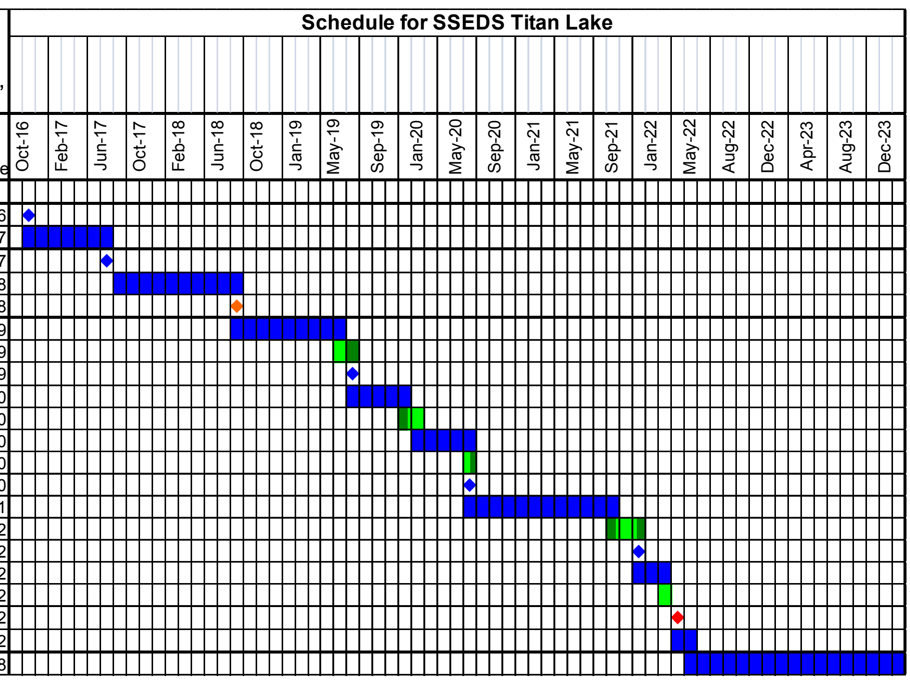
Figure 4-1 provides a feasible schedule for all options of the Titan Lake Probe mission. The mission complexity falls between a basic mission similar to a Discovery mission and a complex or large-directed mission. The reference schedules used for this study were derived from the JPL mission schedule database, which extends back to the Voyager mission.

The Titan Lake Probe mission has no direct analogies; the closest analogy is Phoenix, but with increased complexity and some new engineering. The mission comprises three elements—cruise, EDL, and a lander. Landing and operating on a methane lake has never been done; therefore, additional analysis and engineering would be required beyond previous lander missions.

No major schedule drivers or long-lead items need to be addressed beyond the proposed schedule. Table 4-1 provides key phase durations for the project. Since this mission is being proposed as a New Frontiers–competed mission, all instruments and flight elements are planned to be delivered at the beginning of system-level integration and test.

Basic Mission (Mostly inherited HW & SW, some new technology, etc.)

Phase	Start Date	End Date
1143 SSEDS Titan Lake 2010-01 Option 2		
MCR	12/01/16	12/03/16
Ph A Project Definition	12/01/16	08/28/17
PMSR	09/01/17	09/03/17
Ph B Preliminary Design	09/06/17	09/01/18
CR/PDR/Tech Cutoff	09/01/18	09/04/18
Ph C Design	09/01/18	07/28/19
Margin	07/28/19	09/01/19
CDR	09/01/19	09/04/19
Ph C Fabrication	09/04/19	02/16/20
Margin	02/16/20	03/02/20
Ph C S/S I&T	03/02/20	08/14/20
Margin	08/14/20	09/01/20
ARR (ph D)	09/01/20	09/04/20
Proj I&T (ATLO)	09/04/20	11/03/21
Margin	11/03/21	02/01/22
PSR	02/01/22	02/04/22
Launch Ops	02/04/22	04/14/22
Margin	04/14/22	05/01/22
Launch	05/01/22	05/22/22
L+30-end Ph D	05/22/22	06/21/22
Phase E	06/21/22	07/19/28



Legend	
Normal Task	
Margin	
Long Lead Item	
Project Level Review	◆◆◆
PDR/Tech cutoff	◆◆◆
Launch	◆◆◆

Figure 4-1. Mission Schedule

Table 4-1. Key Phase Durations

Project Phase	Duration (Months)
Phase A – Conceptual Design	9
Phase B – Preliminary Design	12
Phase C – Detailed Design	24
Phase D – Integration & Test	21
Phase E – Primary Mission Operations	74 (Option 2) 110 (Option 3 and 4)
Phase F – Extended Mission Operations	4
Start of Phase B to PDR	12
Start of Phase B to CDR	24
Start of Phase B to delivery of instrument #1	36
Start of Phase B to delivery of instrument #2	36
Start of Phase B to delivery of instrument #n	36
Start of Phase B to delivery of flight element #1	36
Start of Phase B to delivery of flight element #2	36
Start of Phase B to delivery of flight element #n	36
System-level Integration & Test	17
Project total funded schedule reserve	5.5
Total development time Phase B–D	57

Technology Development Plan

The plan to mature the technologies depends on the instrument type, but would require PIDDP, ASTID, and dedicated mid-TRL level funds to accomplish the development to TRL 6. Some instruments would encounter the 95 K temperatures on Titan and consequently would need to be tested and qualified in that regime. The temperature cycling is expected to be minimal during operations because of the stable temperatures found on Titan's surface. Other instruments (e.g., the mass spectrometers) would be housed in WEBs, but the sample acquisition and transfer systems would be exposed to the lake environment. To test a prototype of the complete instrument would therefore require testing in a Titan simulation chamber. Testing the instrument systems in an appropriate environment would require building a test chamber to accommodate both the instruments and the sample acquisition system. This test chamber would need development and careful consideration for all the intricacies of housing a cryogenic liquid in a cryogenic chamber. A conservative estimate for this chamber is approximately $5M.

The Pre-Phase A costs are provided in column three of Table 4-2. Note that the costs for the lower TRL sample handling systems are much higher than the instruments themselves. This is because of the extreme environments experienced by the sample acquisition device. One side would have to accept the liquid methane/ethane at 94 K while the other side would experience the warmer temperature of the thermal enclosure.

Phase A costs would cover the qualification (thermal cycling, launch loads, EMI/EMC and acoustic loads, etc.) of the instrument subsystems and components and any project-specific requirements, etc. Note that the test plan would need to envelope conditions experienced during launch, cruise, and then also during operations, with their attending margins. The assumption is that the thermal environment would be stable for the instruments during each of these periods. Note, also that the costs quoted are ROM and are approximately 10% of the total expected costs of the instruments (which is consistent with JPL experience).

Table 4-2. In-Situ Titan Instruments Technology Development Matrix

In-Situ Instruments	TRL Level	Pre-Phase A Costs	Phase A Costs	Critical Aspects Needed for Development to TRL 6
Hi-res GC-GC MS (1–300 Da mass range with resolution = 10,000)	GC-GC = 3 MS = 5	$10M over 3 years	$8M	Brassboard developed, but complete system prototype with sample handling needed plus testing system in environment. Flight heritage: Rosina on Rosetta. Mass and power reductions required.
Sample handling system	2	$12M over 3 years	$7M	Needs design and development from concepts operational in ocean research on Earth.
Low res & isotope ratio GC-GC MS (1–150 Da mass range with 1,000 resolution)	GC-GC = 3 MS = 4	$15M over 4 years	$8M	Sample preparation more complex and requires development; isotope MS needs development from breadboard to full system. Mass and power reductions required. Testing in environment needed.
Sample handling system, including solids	2	$12M over 3 years	$7M	Needs design and development from concepts operational in ocean research on Earth.
Echo sounder	2	$3M over 3 years	$2M	Methodology and mode of measurement unclear. Instruments exist for Earth applications, but unclear if they can be used with methane/ethane.
Turbidimeter	3	$2M over 2 years	$1M	Camera and light source. Development needed to adapt to Titan's lake material and testing in environment. Heritage: Huygens plus MSL.
[Mast] relative humidity (TDL)	3	$2M over 3 years	$3M	Heritage: TLS. More complex in the sense that there are three measurement points needed by three instruments. Environment testing also required.
[Mast] wind speed/press/temp	5 for P, T & 2 for wind speed msmt	$2M over 3 years	$1M	Instruments well understood, but development needed to measure wind speed to 0.01 m/sec accuracy on vert. axis. Heritage: MLS.
DISR (includes descent cameras)	8	$3M over 3 years	$4M	Flown on Huygens but modernization required to accommodate current flight parts. Mass and power reductions required.
Surface cameras	8	$500k over 1 year	$2M	Flown on Huygens but modernization required to accommodate current flight parts. Mass and power reductions required.
Magnetometer	4	$1M over 2 years	$2M	Floating lander needs to be magnetically clean and/or use multiple small magnetometers to subtract floating lander mag. component. Heritage: Cassini.

In-Situ Instruments	TRL Level	Pre-Phase A Costs	Phase A Costs	Critical Aspects Needed for Development to TRL 6
FTIR spectrometer w/ ATR sampling head; range 4,000–400 cm^{-1}, 2 cm^{-1} res	4	$4M over 3 years	$3M	Testing in environment needed. Also movement of optical components at cryogenic temperatures not demonstrated. Mass and power reductions required.
Refractometer	2	$3M over 3 years	$2M	Breadboard demonstration published, but development and testing in lake operations required.
Dielectric constant/permittivity measurement	5	$2M over 3 years	$1M	Electrodes spaced apart from one another, immersed in the liquid. Similar instrument flew on Phoenix as part of MECA. Needs testing in lake environment.
Speed of Sound/densitometer	4	$3M over 3 years	$1M	Based on acoustic transducer and receiver. Breadboards well understood. Need to develop and test in Titan lake environment.
Liquid/gas pressure transducer	8	$300k over 1 year	$0.5M	Simple instrument, flown on Huygens but needs updating with current flight components.
Liquid/gas temperature measurement	8	$300k over 1 year	$0.5M	Simple instrument, flown on Huygens but needs updating with current flight components.
Penetrometer (measures hardness of lake bed)	8	$200k over 1 year	$0.5M	Identical to instrument flown on Huygens but needs updating with current flight components.

Back-Up Plans and Alternatives for the Required Technologies

There are no viable back-up plans or alternatives without reducing the science goals of the mission.

Development Schedule and Constraints

Figure 4-2 provides the development schedule. The only significant constraint on the schedule is the assumed launch date, which would not alter the current schedule. However, an earlier launch date would present some scheduling issues.

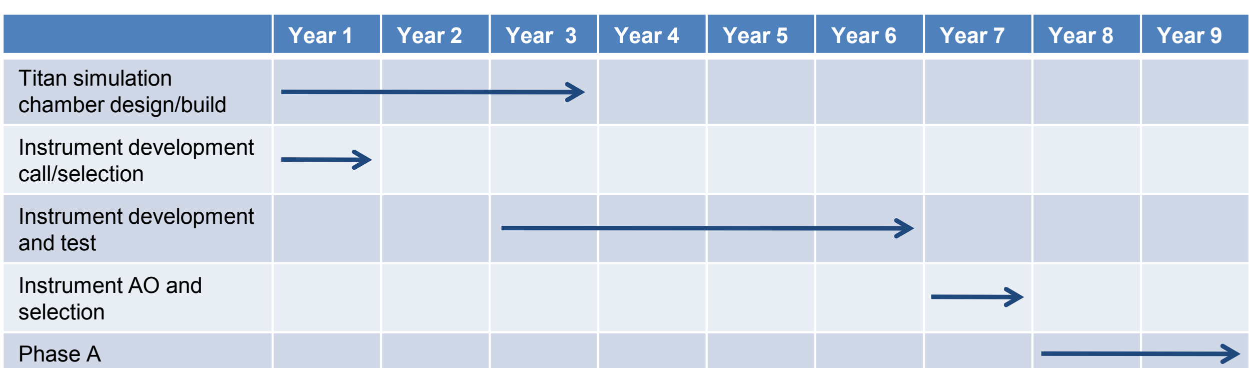


Figure 4-2. Summary Schedule

5. Mission Life-Cycle Cost

Cost Estimate Interpretation Policy, Reserves, and Accuracy

Team X guidelines for this study were to provide independent design and costing analysis for each mission concept. The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, and should be viewed as indicative rather than predictive.

Costing Methodology and Basis of Estimate

The cost estimation process begins with the customer providing the base information for the cost estimating models and defining the mission characteristics, such as:

- Mission architecture
- Payload description
- Master equipment list (MEL) with heritage assumptions
- Functional block diagrams
- Spacecraft/payload resources (mass [kg], power [W], etc.)
- Phase A–F schedule
- Programmatic requirements
- Model specific inputs

JPL has created 33 subsystem cost models, each owned, developed, and operated by the responsible line organization. These models are customized and calibrated using actual experience from completed JPL planetary missions. The models are under configuration management control and are utilized in an integrated and concurrent environment, so that the design and cost parameters are linked.

Cost Estimates

Tables 5-1 through 5-4 provide the cost for each of the four options in detail. The total cost is given by WBS element, based on fiscal year (FY) 2015 funds and the cost per real year (RY) funds for each of the years from project start (FY2017) to completion of Phase F (FY2033). It is assumed that the mission is totally funded by NASA and all significant work is performed in the US.

Table 5-1. Total Mission Cost Funding Profile—Option 1

(FY costs[1] in 2015 dollars, totals in real year and 2015 dollars)

Item	Prior	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	FY2033	Total (Real Yr.)	Total (FY2015)
Cost																				
Phase A concept study (included below)		4.7	9.5																14.2	13.2
Technology development																				
		Phase A - D																		
Mission PM/SE/MA		0.2	0.9	3.4	6.4	6.8	7.0	10.6	13.4	3.5									52.2	43.1
Pre-launch science		0.2	1.1	4.5	8.2	8.8	9.0	13.7	17.4	4.5									67.4	55.6
Instrument PM/SE		0.1	0.6	2.5	4.5	4.9	5.0	7.5	9.6	2.5									37.1	30.6
Floating Lander																				
Hi rez GC-GC MS		0.2	1.4	5.6	10.4	11.1	11.4	17.2	21.8	5.6									84.8	70.0
Rain gauge		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0									0.0	0.0
Surface cameras		0.0	0.2	0.7	1.3	1.3	1.4	2.1	2.6	0.7									10.2	8.4
Descent cameras		0.0	0.1	0.3	0.6	0.6	0.7	1.0	1.2	0.3									4.8	4.0
Turbidimeter		0.0	0.1	0.5	1.0	1.1	1.1	1.7	2.1	0.5									8.1	6.7
Echo sounder		0.0	0.1	0.4	0.7	0.7	0.7	1.1	1.4	0.4									5.5	4.5
Magnetometer		0.0	0.1	0.5	0.9	1.0	1.0	1.5	2.0	0.5									7.6	6.3
LPP instruments		0.0	0.1	0.5	0.8	0.9	0.9	1.4	1.8	0.5									6.9	5.7
[Mast] Relative Humidity		0.1	0.8	3.3	6.1	6.5	6.7	10.1	12.9	3.3									49.9	41.2
[Mast] Wind speed/press/temp		0.0	0.1	0.5	0.9	1.0	1.0	1.5	1.9	0.5									7.3	6.0
Descent instruments		0.2	1.2	5.0	9.2	9.8	10.1	15.3	19.3	5.0									75.1	62.0
Submersible																				
Low rez GC-GC MS		0.1	0.6	2.2	4.2	4.4	4.6	6.9	8.7	2.3									33.9	28.0
FTIR spectrometer		0.0	0.2	0.8	1.5	1.6	1.7	2.6	3.2	0.8									12.6	10.4
Echo sounder		0.0	0.0	0.1	0.3	0.3	0.3	0.4	0.6	0.1									2.2	1.8
Turbidimeter		0.0	0.1	0.2	0.4	0.4	0.4	0.7	0.8	0.2									3.2	2.7
LPP instruments		0.0	0.0	0.2	0.3	0.4	0.4	0.6	0.7	0.2									2.8	2.3
Flight Element PM/SE		0.3	1.6	6.2	11.5	12.3	12.6	19.1	24.2	6.3									94.1	77.6
Flight Element (Floating Lander)		0.9	5.2	20.9	38.6	41.2	42.3	64.1	81.2	21.0									315.4	260.3
Flight Element (Submersible)		0.3	2.0	7.9	14.7	15.7	16.1	24.4	31.0	8.0									120.2	99.2
Flight Element (Entry System)		0.3	1.6	6.2	11.5	12.3	12.7	19.2	24.3	6.3									94.3	77.8
MSI&T [2]		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0									0.0	0.0
Ground data system dev		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0									0.0	0.0
Navigation & mission design		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0									0.0	0.0
Total dev. w/o reserves		3.2	18.1	72.4	134.1	143.2	147.1	222.6	282.1	73.0									1095.8	904.3
Development reserves		1.6	9.0	36.2	67.0	71.6	73.6	111.3	141.1	36.5									547.9	452.2
Total A–D development cost		4.7	27.1	108.6	201.1	214.9	220.7	333.9	423.2	109.5									1643.7	1356.5
Launch services																			0.0	0.0
										Phase E										
Phase E science										8.5	11.6	11.9	12.2	12.6	12.9	13.3	13.6	4.7	101.3	70.0
Other Phase E cost										0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.0	0.7
Phase E reserves										2.1	2.9	3.0	3.1	3.2	3.3	3.3	3.4	1.2	25.6	17.7
Total Phase E										10.7	14.7	15.1	15.5	15.9	16.3	16.7	17.2	5.9	127.9	88.4
Education/outreach																			0.0	0.0
Other (specify)																			0.0	0
Total Cost	**$**	**$ 4.7**	**$ 27.1**	**$ 108.6**	**$ 201.1**	**$ 214.9**	**$ 220.7**	**$ 333.9**	**$ 423.2**	**$ 120.1**	**$ 14.7**	**$ 15.1**	**$ 15.5**	**$ 15.9**	**$ 16.3**	**$ 16.7**	**$ 17.2**	**$ 5.9**	**$ 1,772**	**$ 1,445**
																			Total Mission Cost	**$ 1,445**

[1] Costs include all costs including any fee

[2] MSI&T - Mission System Integration and Test and preparation for operations

Table 5-2. Total Mission Cost Funding Profile—Option 2

(FY costs[1] in 2015 dollars, totals in real year and 2015 dollars)

Item	Prior	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	Total (Real Yr.)	Total (FY2015)
Cost																
Phase A concept study (included below)		10.8													10.8	10.3
Technology development																
		Phase A - D														
Mission PM/SE/MA		2.5	11.5	23.6	24.9	28.4	17.0								107.9	94.3
Pre-launch science		0.7	3.0	6.2	6.5	7.4	4.4								28.2	24.6
Instrument PM/SE		0.5	2.2	4.5	4.7	5.4	3.2								20.6	18.0
Low rez GC-GC MS		0.7	3.4	7.0	7.4	8.4	5.0								32.0	28.0
Rain gauge		0.0	0.0	0.0	0.0	0.0	0.0								0.1	0.1
Surface cameras		0.2	1.0	2.1	2.2	2.5	1.5								9.7	8.4
Descent cameras		0.1	0.5	1.0	1.1	1.2	0.7								4.6	4.0
Turbidimeter		0.2	0.8	1.7	1.8	2.0	1.2								7.7	6.7
Echo sounder		0.1	0.5	1.1	1.2	1.4	0.8								5.2	4.5
LPP instruments		0.2	0.7	1.4	1.5	1.7	1.0								6.5	5.7
[Mast] Relative Humidity		1.1	5.0	10.3	10.9	12.4	7.4								47.2	41.2
[Mast] Wind speed/press/temp		0.2	0.7	1.5	1.6	1.8	1.1								6.9	6.0
Descent instruments		0.0	0.0	0.0	0.0	0.0	0.0								0.0	0.0
Flight Element PM/SE		1.6	7.2	14.7	15.5	17.7	10.5								67.1	58.7
Flight Element (Floating Lander)		5.2	24.0	49.2	51.8	59.3	35.3								224.8	196.4
Flight Element (Entry System)		1.6	7.3	15.0	15.8	18.1	10.8								68.7	60.1
Flight Element (Cruise Stage)		2.4	10.9	22.4	23.6	27.0	16.1								102.5	89.6
MSI&T [2]		0.5	2.4	5.0	9.0	28.8	17.2								63.0	54.0
Ground data system dev		0.5	2.4	4.8	5.1	5.8	3.5								22.1	19.3
Navigation & mission design		0.3	1.2	2.5	2.6	3.0	1.8								11.5	10.0
Total dev. w/o reserves		18.5	84.9	174.1	187.3	232.7	138.7								836.2	729.5
Development reserves		9.7	44.6	91.3	96.3	110.1	65.6								417.6	364.9
Total A–D development cost		28.3	129.5	265.4	283.5	342.7	204.3								1253.8	1094.4
Launch services			12.9	78.1	82.4	94.2	56.2								323.7	281.0
							Phase E									
Phase E science							2.2	5.5	5.6	5.8	5.9	6.1	5.0	0.1	36.1	27.5
Other Phase E cost							4.6	11.2	11.5	11.8	12.1	12.5	10.2	0.2	74.2	56.5
Phase E reserves							1.7	4.2	4.3	4.4	4.6	4.7	3.8	0.1	27.8	21.2
Total Phase E							8.5	20.9	21.5	22.0	22.6	23.2	19.0	0.4	138.1	105.1
Education/outreach		0.05	0.25	0.51	0.54	0.61	0.37	1.21	1.24	1.28	1.31	1.35	1.10	0.02	9.8	8.1
Other (specify)															0.0	0
Total Cost	**$**	**$ 28.3**	**$ 142.6**	**$ 344.1**	**$ 366.5**	**$ 437.6**	**$ 269.4**	**$ 22.1**	**$ 22.7**	**$ 23.3**	**$ 23.9**	**$ 24.6**	**$ 20.1**	**$ 0.4**	**$ 1,725**	**$ 1,489**
															Total	**$ 1,489**

[1] Costs include all costs including any fee

[2] MSI&T - Mission System Integration and Test <u>and</u> preparation for operations

Table 5-3. Total Mission Cost Funding Profile—Option 3

(FY costs[1] in 2015 dollars, totals in real year and 2015 dollars)

Item	Prior	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	Total (Real Yr.)	Total (FY2015)
Cost																			
Phase A concept study (included below)		3.7	7.3															11.0	10.3
Technology development																			
		Phase A - D																	
Mission PM/SE/MA		0.3	5.3	16.5	24.3	26.7	29.3	7.6										110.0	94.5
Pre-launch science		0.1	1.0	3.2	4.7	5.2	5.7	1.5										21.3	18.3
Instrument PM/SE		0.0	0.4	1.3	1.9	2.1	2.3	0.6										8.7	7.5
Hi rez GC-GC MS		0.2	3.9	12.2	18.0	19.8	21.7	5.6										81.5	70.0
FTIR spectrometer		0.0	0.4	1.4	2.1	2.3	2.5	0.6										9.3	8.0
LPP instruments		0.0	0.3	1.0	1.5	1.7	1.9	0.5										7.0	6.0
Descent camera		0.0	0.3	0.8	1.2	1.4	1.5	0.4										5.6	4.8
Flight Element PM/SE		0.2	3.3	10.2	15.0	16.5	18.1	4.7										67.9	58.4
Flight Element (Submersible)		0.3	5.4	16.9	24.9	27.4	30.0	7.8										112.7	96.8
Flight Element (Entry System)		0.2	3.5	10.8	15.9	17.5	19.2	5.0										72.1	61.9
Flight Element (Cruise Stage)		0.7	11.4	35.7	52.5	57.7	63.3	16.4										237.7	204.3
MSI&T [2]		0.1	1.2	3.9	5.7	16.9	28.6	7.4										63.9	53.9
Ground data system dev		0.1	1.4	4.3	6.3	6.9	7.5	1.9										28.3	24.3
Navigation & mission design		0.0	0.7	2.1	3.1	3.4	3.7	1.0										13.9	11.9
Total dev. w/o reserves		2.4	38.5	120.4	177.2	205.3	235.2	60.9										839.9	720.7
Development reserves		1.3	20.1	63.0	92.7	101.9	111.7	28.9										419.5	360.5
Total A–D development cost		3.7	58.6	183.4	269.8	307.2	346.9	89.7										1259.4	1081.1
Launch services				27.9	57.7	63.4	69.5	18.0										236.6	202.0
								Phase E											
Phase E science								2.0	2.7	2.8	2.9	2.9	3.0	3.1	3.2	3.3	1.7	27.7	19.8
Other Phase E cost								10.6	14.6	15.0	15.4	15.8	16.2	16.7	17.1	17.6	9.2	148.1	106.2
Phase E reserves								3.1	4.3	4.4	4.5	4.6	4.7	4.9	5.0	5.1	2.7	43.3	31.1
Total Phase E								15.7	21.6	22.1	22.7	23.4	24.0	24.6	25.3	26.0	13.7	219.1	157.1
Education/outreach		0.01	0.1	0.4	0.5	0.6	0.7	0.2	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.1	0.6	10.7	8.5
Other (specify)																		0.0	0
Total Cost	**$**	**$ 3.7**	**$ 58.7**	**$ 211.7**	**$ 328.1**	**$ 371.2**	**$ 417.1**	**$ 123.6**	**$ 22.4**	**$ 23.0**	**$ 23.7**	**$ 24.3**	**$ 25.0**	**$ 25.6**	**$ 26.3**	**$ 27.0**	**$ 14.2**	**$ 1,726**	**$ 1,449**
															Total Mission Cost				**$ 1,449**

[1] Costs include all costs including any fee

[2] MSI&T - Mission System Integration and Test and preparation for operations

Table 5-4. Total Mission Cost Funding Profile—Option 4

(FY costs[1] in 2015 dollars, totals in real year and 2015 dollars)

Item	Prior	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	Total (Real Yr.)	Total (FY2015)
Cost																			
Phase A concept study (included below)		3.2	6.4															9.6	8.9
Technology development																			
		Phase A - D																	
Mission PM/SE/MA		0.3	5.0	15.6	23.0	25.3	27.7	7.2										104.1	89.5
Pre-launch science		0.1	0.8	2.6	3.9	4.3	4.7	1.2										17.6	15.1
Instrument PM/SE		0.0	0.3	1.0	1.4	1.6	1.7	0.4										6.4	5.5
Low rez GC-GC MS		0.1	1.6	4.9	7.2	7.9	8.7	2.2										32.6	28.0
LPP instruments		0.0	0.3	1.0	1.5	1.7	1.9	0.5										7.0	6.0
Descent camera		0.0	0.3	0.8	1.2	1.4	1.5	0.4										5.6	4.8
Flight Element PM/SE		0.2	3.3	10.2	15.0	16.5	18.1	4.7										67.9	58.3
Flight Element (Floating Lander)		0.3	4.2	13.2	19.4	21.4	23.4	6.1										87.9	75.6
Flight Element (Entry System)		0.2	3.4	10.6	15.5	17.1	18.7	4.8										70.3	60.4
Flight Element (Cruise Stage)		0.7	11.2	35.0	51.5	56.6	62.1	16.1										233.1	200.3
MSI&T [2]		0.1	1.2	3.9	5.7	17.0	29.0	7.5										64.4	54.3
Ground data system dev		0.1	1.1	3.4	5.1	5.6	6.1	1.6										23.0	19.7
Navigation & mission design		0.0	0.7	2.1	3.1	3.4	3.7	1.0										13.9	11.9
Total dev. w/o reserves		2.1	33.3	104.4	153.6	179.6	207.2	53.6										733.8	629.5
Development reserves		1.1	17.6	55.0	80.9	89.0	97.5	25.2										366.3	314.8
Total A–D development cost		3.2	50.9	159.4	234.5	268.5	304.8	78.8										1100.1	944.3
Launch services				27.9	57.7	63.4	69.5	18.0										236.6	202.0
								Phase E											
Phase E science								1.6	2.2	2.3	2.3	2.4	2.4	2.5	2.6	2.6	1.4	22.3	16.0
Other Phase E cost								10.6	14.5	14.9	15.3	15.7	16.1	16.6	17.0	17.5	9.2	147.3	105.7
Phase E reserves								3.0	4.1	4.2	4.3	4.4	4.6	4.7	4.8	4.9	2.6	41.6	29.8
Total Phase E								15.1	20.8	21.4	21.9	22.5	23.1	23.8	24.4	25.1	13.2	211.2	151.5
Education/outreach		0.01	0.10	0.33	0.48	0.53	0.58	0.15	0.77	0.79	0.82	0.84	0.86	0.88	0.91	0.93	0.49	9.5	7.5
Other (specify)																		0.0	0
Total Cost	**$**	**$ 3.2**	**$ 51.0**	**$ 187.7**	**$ 292.7**	**$ 332.5**	**$ 374.9**	**$ 112.1**	**$ 21.6**	**$ 22.1**	**$ 22.7**	**$ 23.4**	**$ 24.0**	**$ 24.6**	**$ 25.3**	**$ 26.0**	**$ 13.7**	**$ 1,557**	**$ 1,305**
																	Total Mission Cost		**$ 1,305**

[1] Costs include all costs including any fee

[2] MSI&T - Mission System Integration and Test <u>and</u> preparation for operations

Appendix A. Acronyms

ADR	adaptive data rate
AOA	angle of attack
AIMS	advanced-integrated micro-sun sensors
AO	announcement of opportunity
ASI	atmospheric structure instrument
ASRG	advanced stirling radioisotope generators
ASTID	Astrobiology Science and Technology Instrument Development
ATR	attenuated total reflectance
BOL	beginning of life
BWG	beam waveguide
C&DH	command and data handling
CBE	current best estimate
CCSDS	Consultative Committee for Space Data Systems
CDR	Critical Design Review
CFDP	CCSDS File Delivery Protocol
CML	concept maturity level
CR	Concept Review
DGB	disk-gap-band
DISR	descent imager/spectral radiometer
DSM	deep-space maneuver
DSN	Deep Space Network
DTE	direct-to-Earth
DTN	Delay Tolerant Networking
EDL	entry, descent, and landing
EFPA	entry flight path angle
EMEJ2000	Earth Mean Equator of J200
EMI	electromagnetic interference
EMC	electromagnetic compatibility
EOL	end of life
EPS	electrical power system
ETM	event timer module
FTIR	Fourier transform infrared
FY	fiscal year
GC-GC MS	two-dimensional gas chromatograph, mass spectrometer
HGA	high-gain antenna
IMU	inertial measurement unit
IR	infrared
JPL	Jet Propulsion Laboratory
LGA	low-gain antenna
LILT	low intensity, low temperature
MLI	multilayer insulation
LPP	lake properties package
MCIC	multilayer ceramic integrated circuit
MECA	Mars Environmental Compatibility Assessment
MER	Mars Exploration Rover
MEV	maximum expected value
MSAP	multimission system architecture platform
MSIA	MSAP system interface assembly
MSL	Mars Science Laboratory
MTIF	MSAP telecommunications interface
MTTF	mean time to failure
NASA	National Aeronautics and Space Administration
NF	New Frontiers
NRC	National Research Council
PA	power assembly
PAM	power analog module
PIDDP	Planetary Instrument Definition and Development
PDR	Preliminary Design Review
POC	point of contact

RF	radio frequency
RHU	radioactive heater units
ROM	rough order-of-magnitude
RY	real year
SSPA	solid-state power amplifier
TiPI	Titan Probe Imager
TCM	trajectory correction maneuver
TDL	tunable diode laser
TE	Titan Explorer
TLS	tunable laser spectrometer
TMS	telecommunications and mission systems
TRL	technology readiness level
TSSM	Titan Saturn System Mission
TWTA	traveling wave tube amplifier
USTA	Universal Space Transponder
VHF	very high frequency
VIS	visible
WBS	work breakdown structure
WEB	warm electronic box

Appendix B. References

[1] Waite, J. Hunter, T. Brockwell, J. Cronenberger, M. Epperley, and J. Pruitt. 3 December 2008. *Titan Submersible Explorer: A low-risk, technically feasible, sub-surface sampling system for Titan's lakes.* Southwest Research Institute, San Antonio, TX.

[2] National Aeronautics and Space Administration. *Ground Rules for Mission Concept Studies in Support of Planetary Decadal Survey, Revision 2.* Released 10 November 2009.

[3] Jet Propulsion Laboratory. 11 December 2006. *Design, Verification/Validation & Ops Principles for Flight Systems (Design Principles), Revision 3.* Document number 43913.

[4] Jet Propulsion Laboratory. 30 September 2008. *Flight Project Practices, Revision 7.* Document number 58032.

Appendix C. Master Equipment List

The following MELs are included in this appendix:

- Flagship Submersible
- Flagship Floating Lander
- Flagship Entry System
- New Frontiers DTE Floating Lander
- New Frontiers DTE Entry System
- New Frontiers DTE Cruise Stage
- New Frontiers Relay Submersible
- New Frontiers Relay Submersible Entry System
- New Frontiers Relay Submersible Cruise Stage
- New Frontiers Relay Floating Lander
- New Frontiers Relay Floating Lander Entry System
- New Frontiers Relay Floating Lander Cruise Stage

Flagship Submersible Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Submersible Mass			**200.7 kg**	**43%**	**286.4 kg**
Stack (w/ Wet Element)			**200.7 kg**	**43%**	**286.4 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**200.7 kg**	**43%**	**286.4 kg**
Carried Elements			**0.0 kg**	**0%**	**0.0 kg**
Submersible Mass			**200.7 kg**	**43%**	**286.4 kg**
Wet Element			**200.7 kg**	**43%**	**286.4 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**200.7 kg**	**43%**	**286.4 kg**
System Contingency			**26.7 kg**	**13%**	
Subsystem Heritage Contingency			**58.5 kg**	**30%**	
Payload			**38.0 kg**	**30%**	**49.4 kg**
Instruments		**5**	**38.0 kg**	**30%**	**49.4 kg**
Low rez GC-GC MS	25.0 kg	1	25.0 kg	30%	32.5 kg
FTIR spectrometer	2.0 kg	1	2.0 kg	30%	2.6 kg
Echo sounder	5.0 kg	1	5.0 kg	30%	6.5 kg
Turbidimeter	2.0 kg	1	2.0 kg	30%	2.6 kg
LPP instruments	4.0 kg	1	4.0 kg	30%	5.2 kg
Additional Payload		**0**	**0.0 kg**	**30%**	**0.0 kg**
Bus			**162.7 kg**	**29%**	**210.2 kg**
Attitude Control		**0**	**0.0 kg**	**0%**	**0.0 kg**
Command & Data		**4**	**2.8 kg**	**30%**	**3.7 kg**
Custom_Special_Function_Board: ETM - Sequencer/Radio I/F	0.7 kg	2	1.4 kg	30%	1.8 kg
Custom_Special_Function_Board: ETM - Instrument I/F	0.7 kg	2	1.4 kg	30%	1.8 kg
Power		**12**	**26.0 kg**	**30%**	**33.8 kg**
Li-CFx (Primary Battery)	5.4 kg	4	21.6 kg	30%	28.1 kg
Chassis	1.8 kg	1	1.8 kg	30%	2.3 kg
Power Conditioning Card - Modeled as Houskeeping DC-DC Converters* Boards	0.4 kg	2	0.8 kg	30%	1.0 kg
Power and Battery Interface Board - Modeled as Battery Control Boards	0.4 kg	2	0.8 kg	30%	1.0 kg
Instrument Load Control Board - Modeled as Diodes* Boards	0.4 kg	2	0.8 kg	30%	1.0 kg
Shielding	0.2 kg	1	0.2 kg	30%	0.3 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**11**	**106.4 kg**	**30%**	**138.3 kg**
Struc. & Mech.		10	98.4 kg	30%	127.9 kg
Internal Primary Structure (66% Stays on Bottom)	17.4 kg	1	17.4 kg	30%	22.6 kg
Secondary Structure (66% Stays on Bottom)	2.7 kg	1	2.7 kg	30%	3.5 kg
Hull (0.7 m Spherical Pressure Vessel) (50% Stays on Bottom (1 Hull))	20.9 kg	2	41.8 kg	30%	54.3 kg
Inter-Module Cylindrical Junction (100% Stays on Bottom)	10.0 kg	1	10.0 kg	30%	13.0 kg
Low Frequency Deployment, Release, and Boom (100% Resurfaces)	1.0 kg	1	1.0 kg	30%	1.3 kg
Inter-Module Separation Hardware (80% Stays on Bottom)	4.0 kg	1	4.0 kg	30%	5.2 kg
Sink Rate Controller (100% Resurfaces)	6.0 kg	1	6.0 kg	30%	7.8 kg
Solid Sampling Tool (100% Stays on Bottom)	12.5 kg	1	12.5 kg	30%	16.3 kg
Integration Hardware (60% Stays on Bottom)	3.0 kg	1	3.0 kg	30%	3.9 kg
Cabling Harness (66% Stays on Bottom)	8.0 kg	1	8.0 kg	30%	10.4 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Telecom		**9**	**10.5 kg**	**19%**	**12.6 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	20%	0.4 kg
VHF Crossed Dipole	1.0 kg	1	1.0 kg	30%	1.3 kg
UST (Single Band)	3.5 kg	2	7.0 kg	20%	8.4 kg
X-band SSPA, RF=15W*	1.5 kg	1	1.5 kg	10%	1.7 kg
X-band Diplexer, moderate isolation	0.4 kg	1	0.4 kg	10%	0.4 kg
Coax Cable, flex (120)	0.1 kg	1	0.1 kg	25%	0.1 kg
Coax Cable, flex (190)	0.1 kg	3	0.3 kg	25%	0.4 kg
Thermal		**121**	**16.9 kg**	**29%**	**21.8 kg**
Multilayer Insulation (MLI)	0.4 kg	10	3.8 kg	30%	4.9 kg
Thermal Surfaces		7	0.2 kg	30%	0.2 kg
General	0.0 kg	7	0.2 kg	30%	0.2 kg
Thermal Conduction Control		2	2.2 kg	30%	2.9 kg
General	0.2 kg	1	0.2 kg	30%	0.3 kg
High Conductance	2.0 kg	1	2.0 kg	30%	2.6 kg
Temperature Sensors		50	0.8 kg	15%	0.9 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
PRT's	0.0 kg	25	0.3 kg	15%	0.3 kg
Thermal Switch	1.0 kg	2	2.0 kg	30%	2.6 kg
RHU's	0.4 kg	10	4.0 kg	30%	5.2 kg
Other Components		40	4.0 kg	30%	5.2 kg
Vacuum Getters	0.1 kg	40	4.0 kg	30%	5.2 kg

Flagship Floating Lander Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Landed Mass			**671.6 kg**	**25%**	**837.0 kg**
Stack (w/ Wet Element)			**671.6 kg**	**25%**	**837.0 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**671.6 kg**	**25%**	**837.0 kg**
Carried Elements			**286.4 kg**	**0%**	**286.4 kg**
Submersible			286.4 kg	0%	286.4 kg
Floating Lander Mass			**385.2 kg**	**43%**	**550.6 kg**
Wet Element			**385.2 kg**	**43%**	**550.6 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**385.2 kg**	**43%**	**550.6 kg**
System Contingency			**58.2 kg**	**15%**	
Subsystem Heritage Contingency			**106.6 kg**	**28%**	
Payload			**62.9 kg**	**30%**	**81.8 kg**
Instruments		**18**	**62.9 kg**	**30%**	**81.8 kg**
Hi rez GC-GC MS	25.0 kg	1	25.0 kg	30%	32.5 kg
Rain gauge	0.1 kg	1	0.1 kg	30%	0.1 kg
Surface cameras	1.4 kg	3	4.2 kg	30%	5.5 kg
Descent cameras	0.3 kg	2	0.6 kg	30%	0.8 kg
Turbidimeter	2.0 kg	1	2.0 kg	30%	2.6 kg
Echo sounder	5.0 kg	1	5.0 kg	30%	6.5 kg
Magnetometer	5.0 kg	1	5.0 kg	30%	6.5 kg
LPP instruments	4.0 kg	1	4.0 kg	30%	5.2 kg
[Mast] Relative Humidity	2.0 kg	3	6.0 kg	30%	7.8 kg
[Mast] Wind speed/press/temp	1.0 kg	3	3.0 kg	30%	3.9 kg
Descent instruments	8.0 kg	1	8.0 kg	30%	10.4 kg
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**322.3 kg**	**27%**	**410.6 kg**
Attitude Control		**8**	**14.3 kg**	**27%**	**18.1 kg**
Accelerometers	0.1 kg	4	0.3 kg	0%	0.3 kg
Saturn Camera	5.0 kg	1	5.0 kg	30%	6.5 kg
Camera Gimbal Drive Electronics	1.0 kg	2	2.0 kg	10%	2.2 kg
Radar altimeter	7.0 kg	1	7.0 kg	30%	9.1 kg
Command & Data		**24**	**25.0 kg**	**7%**	**26.7 kg**
Processor: RAD750	0.6 kg	2	1.1 kg	5%	1.2 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg	5%	1.5 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg	5%	1.5 kg
General_I_F: MSIA	0.7 kg	4	2.8 kg	5%	3.0 kg
General_I_F: MCIC	0.7 kg	2	1.3 kg	17%	1.5 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg	17%	1.5 kg
Power: CEPCU	1.2 kg	4	4.6 kg	10%	5.1 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	2	1.7 kg	8%	1.8 kg
Chassis: CDH chassis (8 slot)	3.8 kg	2	7.7 kg	2%	7.8 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg	6%	1.7 kg
Power		**17**	**80.5 kg**	**30%**	**104.6 kg**
Advanced Li-Ion (Secondary Battery)	5.9 kg	4	23.7 kg	30%	30.8 kg
Advanced Stirling (ASRG-850C)	22.0 kg	2	44.0 kg	30%	57.1 kg
Chassis	1.6 kg	1	1.6 kg	30%	2.1 kg
Shunt Discharge Slice & Power Switch Chard Board (PSC) - Modeled as Load Switches Boards	1.4 kg	3	4.2 kg	30%	5.5 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Power Conditioning Board (PCU) - Modeled as Houskeeping DC-DC Converters Boards	1.4 kg	1	1.4 kg	30%	1.8 kg
Power Bus Contoller Board (PBC)- Modeled as Power/Shunt Control* Boards	1.1 kg	2	2.2 kg	30%	2.9 kg
ARPS (Stirling) Controller* Boards	0.8 kg	2	1.6 kg	30%	2.1 kg
Power Junction Box Slice - Modeled as Diodes Boards	0.8 kg	1	0.8 kg	30%	1.0 kg
Shielding	1.1 kg	1	1.1 kg	30%	1.4 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**8**	**157.4 kg**	**30%**	**204.6 kg**
Struc. & Mech.		7	127.5 kg	30%	165.8 kg
Internal Primary Structure	37.9 kg	1	37.9 kg	30%	49.3 kg
Secondary Structure	4.5 kg	1	4.5 kg	30%	5.9 kg
Hull	71.1 kg	1	71.1 kg	30%	92.4 kg
Submersible Separation System	6.0 kg	1	6.0 kg	30%	7.8 kg
Instrument Mast	4.0 kg	1	4.0 kg	30%	5.2 kg
Low Frequency Deployment, Release, and Boom	1.0 kg	1	1.0 kg	30%	1.3 kg
Integration Hardware	3.0 kg	1	3.0 kg	30%	3.9 kg
Cabling Harness	29.9 kg	1	29.9 kg	30%	38.9 kg
Telecom		**29**	**17.1 kg**	**19%**	**20.4 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	20%	0.4 kg
VHF Crossed Dipole	1.0 kg	1	1.0 kg	30%	1.3 kg
UST (Dual Band)	4.5 kg	2	9.0 kg	20%	10.8 kg
X-band SSPA, RF=15W*	1.5 kg	2	3.0 kg	10%	3.3 kg
Hybrid Coupler	0.0 kg	1	0.0 kg	10%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	10%	0.8 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	1	0.4 kg	10%	0.4 kg
Coax Transfer Switch (CXS)	0.1 kg	2	0.3 kg	10%	0.3 kg
Coax Cable, flex (120)	0.1 kg	3	0.2 kg	25%	0.2 kg
Coax Cable, flex (190)	0.1 kg	10	1.1 kg	25%	1.4 kg
WR-112 WG, rigid (Al)	0.3 kg	4	1.2 kg	25%	1.6 kg
Thermal		**143**	**28.0 kg**	**30%**	**36.3 kg**
Insulation (Aero-Gel)+ (MLI)	1.0 kg	10	10.0 kg	30%	13.0 kg
Thermal Surfaces		15	0.4 kg	30%	0.5 kg
General	0.0 kg	15	0.4 kg	30%	0.5 kg
Thermal Conduction Control		3	4.4 kg	30%	5.7 kg
General	0.4 kg	1	0.4 kg	30%	0.5 kg
High Conductance	2.0 kg	2	4.0 kg	30%	5.2 kg
Heaters		10	0.5 kg	30%	0.7 kg
Custom	0.1 kg	10	0.5 kg	30%	0.7 kg
Temperature Sensors		50	0.8 kg	15%	0.9 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
PRT's	0.0 kg	25	0.3 kg	15%	0.3 kg
Heat Pipes		10	3.0 kg	30%	3.9 kg
CCHP (2-D Bends)	0.3 kg	10	3.0 kg	30%	3.9 kg
Thermal Switch	1.0 kg	5	5.0 kg	30%	6.5 kg
Other Components		40	4.0 kg	30%	5.2 kg
Vacuum Getter	0.1 kg	40	4.0 kg	30%	5.2 kg

Flagship Entry System Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Entry Mass			**1225.5 kg**	**14%**	**1392.5 kg**
Stack (w/ Wet Element)			**1225.5 kg**	**14%**	**1392.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**1225.5 kg**	**14%**	**1392.5 kg**
Carried Elements			**837.0 kg**	**0%**	**837.0 kg**
Floating Lander and Submersible			837.0 kg	0%	837.0 kg
Entry System Mass			**388.5 kg**	**43%**	**555.5 kg**
Wet Element			**388.5 kg**	**43%**	**555.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**388.5 kg**	**43%**	**555.5 kg**
System Contingency			**50.7 kg**	**13%**	
Subsystem Heritage Contingency			**116.4 kg**	**30%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**388.5 kg**	**30%**	**504.9 kg**
Attitude Control		**0**	**0.0 kg**	**0%**	**0.0 kg**
Command & Data		**2**	**1.4 kg**	**30%**	**1.8 kg**
Custom_Special_Function_Board: ETM -	0.7 kg	2	1.4 kg	30%	1.8 kg
Power		**9**	**12.7 kg**	**30%**	**16.5 kg**
Thermal Battery (Thermal Battery)	2.8 kg	3	8.4 kg	30%	10.9 kg
Chassis	1.0 kg	1	1.0 kg	30%	1.2 kg
Instrument Load Control Card - Modeled as Load Switches Boards	0.4 kg	1	0.4 kg	30%	0.5 kg
Thruster Drivers* Boards	0.5 kg	0		30%	
Pyro Switches* Boards	1.1 kg	2	2.2 kg	30%	2.9 kg
Power Conditioning Board - Modeled as Houskeeping DC-DC Converters* Boards	0.4 kg	1	0.4 kg	30%	0.5 kg
Shielding	0.3 kg	1	0.3 kg	30%	0.4 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**4**	**337.7 kg**	**30%**	**438.9 kg**
Struc. & Mech.		3	330.9 kg	30%	430.2 kg
Heat Shield and Backshell	253.6 kg	1	253.6 kg	30%	329.7 kg
Parachute	73.4 kg	1	73.4 kg	30%	95.5 kg
Balance Mass	3.9 kg	1	3.9 kg	30%	5.1 kg
Cabling Harness	6.8 kg	1	6.8 kg	30%	8.8 kg
Telecom		**3**	**1.0 kg**	**24%**	**1.2 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	20%	0.4 kg
WR-112 WG, rigid (Al)	0.4 kg	2	0.7 kg	25%	0.9 kg
Thermal		**125**	**35.7 kg**	**30%**	**46.4 kg**
Multilayer Insulation (MLI)	1.5 kg	16	24.0 kg	30%	31.2 kg
Thermal Surfaces		21	0.5 kg	30%	0.7 kg
General	0.0 kg	21	0.5 kg	30%	0.7 kg
Thermal Conduction Control		7	0.5 kg	30%	0.7 kg
General	0.5 kg	1	0.5 kg	30%	0.7 kg
Isolation (G-10)	0.0 kg	6	0.0 kg	30%	0.0 kg
Heaters		10	0.5 kg	30%	0.7 kg
Custom	0.1 kg	10	0.5 kg	30%	0.7 kg
Temperature Sensors		25	0.5 kg	15%	0.6 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Thermostats		10	0.2 kg	15%	0.2 kg
Mechanical	0.0 kg	10	0.2 kg	15%	0.2 kg
Heat Pipes		30	4.5 kg	30%	5.9 kg
VCHP	0.2 kg	30	4.5 kg	30%	5.9 kg
Other Components		6	5.0 kg	30%	6.5 kg
Heat Pipe Accumulator	0.2 kg	2	0.4 kg	30%	0.5 kg
Heat Pipe Collector Plate	0.5 kg	2	1.0 kg	30%	1.3 kg
Shunt Radiator	1.8 kg	2	3.6 kg	30%	4.7 kg

New Frontiers DTE Floating Lander Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Landed Mass			**378.1 kg**	**42%**	**538.1 kg**
Stack (w/ Wet Element)			**378.1 kg**	**42%**	**538.1 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**378.1 kg**	**42%**	**538.1 kg**
Carried Elements			**0.0 kg**	**0%**	**0.0 kg**
Floating Lander Mass			**378.1 kg**	**42%**	**538.1 kg**
Wet Element			**378.1 kg**	**42%**	**538.1 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**378.1 kg**	**42%**	**538.1 kg**
System Contingency			**56.7 kg**	**16%**	
Subsystem Heritage Contingency			**97.3 kg**	**27%**	
Payload			**57.9 kg**	**30%**	**75.3 kg**
Instruments		**15**	**57.9 kg**	**30%**	**75.3 kg**
Low rez GC-GC MS	25.0 kg	1	25.0 kg	30%	32.5 kg
Rain gauge	0.1 kg	1	0.1 kg	30%	0.1 kg
Surface cameras	1.4 kg	3	4.2 kg	30%	5.5 kg
Descent cameras	0.3 kg	2	0.6 kg	30%	0.8 kg
Turbidimeter	2.0 kg	1	2.0 kg	30%	2.6 kg
Echo sounder	5.0 kg	1	5.0 kg	30%	6.5 kg
LPP instruments	4.0 kg	1	4.0 kg	30%	5.2 kg
[Mast] Relative Humidity	2.0 kg	3	6.0 kg	30%	7.8 kg
[Mast] Wind speed/press/temp	1.0 kg	3	3.0 kg	30%	3.9 kg
Descent instruments	8.0 kg	1	8.0 kg	30%	10.4 kg
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**320.2 kg**	**27%**	**406.1 kg**
Attitude Control		**11**	**4.6 kg**	**15%**	**5.2 kg**
Sun Sensors	0.1 kg	6.0	0.3 kg	30%	0.4 kg
IMUs	0.8 kg	2.0	1.5 kg	10%	1.7 kg
HGA Gimbal Drive Electronics	1.0 kg	2.0	2.0 kg	10%	2.2 kg
Shielding:	0.8 kg	1.0	0.8 kg	30%	1.0 kg
Command & Data		**26**	**26.5 kg**	**8%**	**28.5 kg**
Processor: RAD750	0.6 kg	2	1.1 kg	5%	1.2 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg	5%	1.5 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg	5%	1.5 kg
General_I_F: MSIA	0.7 kg	4	2.8 kg	5%	3.0 kg
General_I_F: MCIC	0.7 kg	2	1.3 kg	17%	1.5 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg	17%	1.5 kg
Power: CEPCU	1.2 kg	4	4.6 kg	10%	5.1 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	2	1.7 kg	8%	1.8 kg
Chassis: CDH chassis (8 slot)	3.8 kg	2	7.7 kg	2%	7.8 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg	6%	1.7 kg
Custom_Special_Function_Board: Event Timer Module (ETM)	0.7 kg	2	1.4 kg	30%	1.8 kg
Power		**17**	**97.6 kg**	**30%**	**126.9 kg**
Advanced Li-Ion (Secondary Battery)	5.9 kg	7	41.4 kg	30%	53.8 kg
Advanced Stirling (ASRG-850C)	22.0 kg	2	44.0 kg	30%	57.1 kg
Chassis	1.4 kg	1	1.4 kg	30%	1.8 kg
Power Switch Card Board (PSC) - Modeled as Load Switches Boards	0.9 kg	3	2.7 kg	30%	3.5 kg
Power Conditioning Board (PCU) - Modeled as Houskeeping DC-DC Converters* Boards	1.1 kg	1	1.1 kg	30%	1.4 kg
Lander Power Interface Slice & Junction Box - Modeled as Power/Shunt Control* Boards	1.8 kg	2	3.6 kg	30%	4.7 kg
Both ETM (Pwr conditioning & instrument boards) - Modeled as Battery Control Boards	0.8 kg	1	0.8 kg	30%	1.0 kg
ARPS (Stirling) Controller* Boards	0.8 kg	2	1.6 kg	30%	2.1 kg
Shielding	1.0 kg	1	1.0 kg	30%	1.3 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Mechanical		**7**	**152.2 kg**	**30%**	**197.9 kg**
Struc. & Mech.		6	126.6 kg	30%	164.5 kg
Internal Primary Structure	29.3 kg	1	29.3 kg	30%	38.0 kg
Secondary Structure	3.6 kg	1	3.6 kg	30%	4.6 kg
Antenna Gimbal Assemblies	6.0 kg	1	6.0 kg	30%	7.8 kg
Hull (Includes Radar Transparent Dome)	78.7 kg	1	78.7 kg	30%	102.3 kg
Instrument Mast (Includes Release, Deployment, and Fin)	7.0 kg	1	7.0 kg	30%	9.1 kg
Integration Hardware	2.0 kg	1	2.0 kg	30%	2.7 kg
Cabling Harness	25.6 kg	1	25.6 kg	30%	33.3 kg
Telecom		**32**	**21.6 kg**	**14%**	**24.6 kg**
X/X-HGA 0.75m diam Parabolic	2.4 kg	1	2.4 kg	20%	2.9 kg
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	30%	0.4 kg
UST (Single Band)	3.5 kg	2	7.0 kg	20%	8.4 kg
X-band TWTA, RF=25W	3.0 kg	2	6.0 kg	10%	6.6 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	2	0.8 kg	10%	0.8 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	10%	0.1 kg
Hybrid Coupler	0.0 kg	1	0.0 kg	10%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	10%	0.8 kg
X-band Rotary Joint	0.2 kg	2	0.3 kg	20%	0.4 kg
X-band Isolator	0.5 kg	2	1.0 kg	20%	1.2 kg
Coax Cable, flex (120)		0		0%	
Coax Cable, flex (190)	0.1 kg	10	1.1 kg	0%	1.1 kg
WR-112 WG, rigid (Al)	0.3 kg	6	1.9 kg	0%	1.9 kg
Thermal		**130**	**17.8 kg**	**29%**	**23.0 kg**
Thermal Surfaces		11	0.3 kg	30%	0.4 kg
General	0.0 kg	11	0.3 kg	30%	0.4 kg
Thermal Conduction Control		3	2.4 kg	30%	3.1 kg
General	0.4 kg	1	0.4 kg	30%	0.5 kg
High Conductance	1.0 kg	2	2.0 kg	30%	2.6 kg
Heaters		10	0.5 kg	30%	0.7 kg
Custom	0.1 kg	10	0.5 kg	30%	0.7 kg
Temperature Sensors		50	0.8 kg	15%	0.9 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
PRT's	0.0 kg	25	0.3 kg	15%	0.3 kg
Heat Pipes		10	3.0 kg	30%	3.9 kg
CCHP (2-D Bends)	0.3 kg	10	3.0 kg	30%	3.9 kg
Thermal Switch	1.0 kg	5	5.0 kg	30%	6.5 kg
Other Components		41	5.9 kg	30%	7.7 kg
Vacuum Getters	0.1 kg	40	4.0 kg	30%	5.2 kg
Aero-Gel Insulation	1.9 kg	1	1.9 kg	30%	2.5 kg

New Frontiers DTE Entry System Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Entry Mass			**786.0 kg**	**14%**	**892.6 kg**
Stack (w/ Wet Element)			**786.0 kg**	**14%**	**892.6 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**786.0 kg**	**14%**	**892.6 kg**
Carried Elements			**538.1 kg**	**0%**	**538.1 kg**
Floating Lander			538.1 kg	0%	538.1 kg
Entry System Mass			**247.9 kg**	**43%**	**354.5 kg**
Wet Element			**247.9 kg**	**43%**	**354.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**247.9 kg**	**43%**	**354.5 kg**
System Contingency			**32.6 kg**	**13%**	
Subsystem Heritage Contingency			**74.0 kg**	**30%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**247.9 kg**	**30%**	**321.9 kg**
Attitude Control		**2**	**1.1 kg**	**17%**	**1.3 kg**
IMU	0.8 kg	1.0	0.8 kg	10%	0.8 kg
Shielding:	0.4 kg	1.0	0.4 kg	30%	0.5 kg
Command & Data		**0**	**0.0 kg**	**0%**	**0.0 kg**
Power		**8**	**7.0 kg**	**30%**	**9.0 kg**
Thermal Battery (Thermal Battery)	1.1 kg	3	3.4 kg	30%	4.4 kg
Chassis	0.7 kg	1	0.7 kg	30%	0.9 kg
Pyro Switches* Boards	1.1 kg	2	2.2 kg	30%	2.9 kg
Power & Battery Interface Board - Modeled as Houskeeping DC-DC Converters* Boards	0.4 kg	1	0.4 kg	30%	0.5 kg
Shielding	0.3 kg	1	0.3 kg	30%	0.4 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**4**	**209.4 kg**	**30%**	**272.2 kg**
Struc. & Mech.		3	204.0 kg	30%	265.2 kg
Heatshield and Backshell	156.3 kg	1	156.3 kg	30%	203.2 kg
Parachute	45.3 kg	1	45.3 kg	30%	58.8 kg
Balance Mass	2.5 kg	1	2.5 kg	30%	3.2 kg
Cabling Harness	5.4 kg	1	5.4 kg	30%	7.0 kg
Telecom		**0**	**0.0 kg**	**0%**	**0.0 kg**
Thermal		**116**	**30.4 kg**	**29%**	**39.3 kg**
Multilayer Insulation (MLI)	1.5 kg	16	24.0 kg	30%	31.2 kg
Thermal Surfaces		15	0.4 kg	0%	0.4 kg
General	0.0 kg	15	0.4 kg	0%	0.4 kg
Thermal Conduction Control		7	0.3 kg	30%	0.4 kg
General	0.3 kg	1	0.3 kg	30%	0.4 kg
Isolation (G-10)	0.0 kg	6	0.0 kg	30%	0.0 kg
Heaters		10	0.5 kg	30%	0.7 kg
Custom	0.1 kg	10	0.5 kg	30%	0.7 kg
Temperature Sensors		25	0.5 kg	15%	0.6 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
Thermostats		10	0.2 kg	15%	0.2 kg
Mechanical	0.0 kg	10	0.2 kg	15%	0.2 kg
Heat Pipes		30	4.5 kg	30%	5.9 kg
VCHP	0.2 kg	30	4.5 kg	30%	5.9 kg

New Frontiers DTE Cruise Stage Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Launch Mass			**3656.9 kg**	**6%**	**3875.7 kg**
Launch Vehicle PLA			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Wet Element)			**3656.9 kg**	**6%**	**3875.7 kg**
Useable Propellant			**2255.3 kg**	**0%**	**2255.3 kg**
Stack (w/ Dry Element)			**1401.6 kg**	**16%**	**1620.4 kg**
Carried Elements			**892.6 kg**	**0%**	**892.6 kg**
Entry System and Lander			892.6 kg	0%	892.6 kg
Carrier Stage Mass			**509.0 kg**	**43%**	**727.8 kg**
Wet Element			**2764.2 kg**	**8%**	**2983.1 kg**
Total Propellant			**2255.3 kg**	**0%**	**2255.3 kg**
System 1: Biprop			**2255.3 kg**	**0%**	**2255.3 kg**
Dry Element			**509.0 kg**	**43%**	**727.8 kg**
System Contingency			**106.1 kg**	**21%**	
Subsystem Heritage Contingency			**112.8 kg**	**22%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**509.0 kg**	**22%**	**621.7 kg**
Attitude Control		**8**	**4.7 kg**	**11%**	**5.2 kg**
Sun Sensors	0.1 kg	3.0	0.2 kg	30%	0.2 kg
Star Trackers	1.5 kg	2.0	3.0 kg	0%	3.0 kg
Engine Gimbal Drive Electronics	0.6 kg	2.0	1.2 kg	30%	1.5 kg
Shielding:	0.4 kg	1.0	0.4 kg	30%	0.5 kg
Command & Data		**2**	**1.6 kg**	**6%**	**1.7 kg**
Analog_I_F: MREU	0.8 kg	2	1.6 kg	6%	1.7 kg
Power		**12**	**28.7 kg**	**30%**	**37.3 kg**
Advanced Li-Ion (Secondary Battery)	5.9 kg	3	17.8 kg	30%	23.1 kg
Chassis	2.0 kg	1	2.0 kg	30%	2.6 kg
Power Switch Cards & Shunt Discharge Slice - Modeled as Load Switches Boards	1.1 kg	2	2.1 kg	30%	2.8 kg
GN&C I/F & Prop Drivers (GID) - Modeled as Thruster Drivers* Boards	0.6 kg	1	0.6 kg	30%	0.8 kg
Power Conditioning ACU PCU - Modeled as Houskeeping DC-DC Converters* Boards	1.1 kg	1	1.1 kg	30%	1.4 kg
Shunt Slice - Modeled as Power/Shunt Control* Boards	1.4 kg	2	2.8 kg	30%	3.6 kg
Power Junction Box - Modeled as Diodes* Boards	1.4 kg	1	1.4 kg	30%	1.8 kg
Shielding	0.8 kg	1	0.8 kg	30%	1.1 kg
Propulsion		**82**	**136.4 kg**	**2%**	**139.5 kg**
System 1: Biprop		82	136.4 kg	2%	139.5 kg
Hardware		82	136.4 kg	2%	139.5 kg
Gas Service Valve	0.2 kg	4	0.9 kg	2%	0.9 kg
HP Latch Valve	0.4 kg	8	2.8 kg	2%	2.9 kg
HP Transducer	0.3 kg	2	0.5 kg	2%	0.6 kg
Gas Filter	0.4 kg	2	0.8 kg	2%	0.8 kg
Press Regulator	0.7 kg	2	1.5 kg	2%	1.5 kg
Temp. Sensor	0.0 kg	3	0.0 kg	2%	0.0 kg
quad check valve	0.1 kg	2	0.2 kg	2%	0.2 kg
Liq. Service Valve	0.3 kg	2	0.6 kg	2%	0.6 kg
Test Service Valve	0.2 kg	2	0.5 kg	2%	0.5 kg
LP Transducer	0.3 kg	5	1.4 kg	2%	1.4 kg
Liq. Filter	0.5 kg	2	0.9 kg	2%	0.9 kg
LP Latch Valve	0.4 kg	8	2.8 kg	2%	2.9 kg
Mass Flow Control	0.0 kg	2	0.1 kg	2%	0.1 kg
Temp. Sensor	0.0 kg	14	0.1 kg	2%	0.1 kg
Lines, Fittings, Misc.	2.5 kg	1	2.5 kg	0%	2.5 kg
DM Monoprop Thrusters 1	0.3 kg	12	4.0 kg	2%	4.0 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Biprop Main Engine	5.8 kg	1	5.8 kg	10%	6.3 kg
Fuel Pressurant Tank	10.0 kg	2	20.0 kg	2%	20.4 kg
Ox Pressurant Tank	10.0 kg	2	20.0 kg	2%	20.4 kg
Fuel Tanks	18.4 kg	2	36.8 kg	2%	37.5 kg
Oxidizer Tanks	17.2 kg	2	34.3 kg	2%	35.0 kg
User Defined	0.0 kg	1	0.0 kg	0%	0.0 kg
Pressurant			0.0 kg	0%	0.0 kg
Residuals			0.0 kg	0%	0.0 kg
Mechanical		**6**	**265.0 kg**	**30%**	**344.4 kg**
Struc. & Mech.		4	227.5 kg	30%	295.7 kg
Primary Structure	191.8 kg	1	191.8 kg	30%	249.3 kg
Secondary Structure	13.3 kg	1	13.3 kg	30%	17.2 kg
Thruster Gimbal	9.0 kg	1	9.0 kg	30%	11.7 kg
Integration Hardware	13.4 kg	1	13.4 kg	30%	17.5 kg
Adapter, Spacecraft side	21.3 kg	1	21.3 kg	30%	27.8 kg
Cabling Harness	16.1 kg	1	16.1 kg	30%	21.0 kg
Telecom		**6**	**6.4 kg**	**22%**	**7.8 kg**
X/X-HGA 0.75m diam Parabolic	2.4 kg	1	2.4 kg	20%	2.9 kg
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	20%	0.4 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	1	0.4 kg	10%	0.4 kg
WR-112 WG, rigid (Al)	1.1 kg	3	3.3 kg	25%	4.1 kg
Thermal		**312**	**66.3 kg**	**29%**	**85.8 kg**
Multilayer Insulation (MLI)	0.4 kg	58	21.7 kg	30%	28.1 kg
Thermal Surfaces		42	1.1 kg	30%	1.4 kg
General	0.0 kg	42	1.1 kg	30%	1.4 kg
Thermal Conduction Control		1	0.6 kg	30%	0.8 kg
General	0.6 kg	1	0.6 kg	30%	0.8 kg
Heaters		64	4.4 kg	30%	5.7 kg
Custom	0.1 kg	40	2.0 kg	30%	2.6 kg
Propulsion Tank Heaters	0.1 kg	16	1.6 kg	30%	2.1 kg
Propulsion Line Heaters	0.1 kg	8	0.8 kg	30%	1.0 kg
Temperature Sensors		100	2.0 kg	15%	2.3 kg
Thermistors	0.0 kg	100	2.0 kg	15%	2.3 kg
Thermostats		20	0.4 kg	15%	0.5 kg
Mechanical	0.0 kg	20	0.4 kg	15%	0.5 kg
Thermal Louvers	1.0 kg	2	2.0 kg	30%	2.5 kg
Thermal Radiator (Area=m2)	10.5 kg	3	31.5 kg	30%	41.0 kg
Heat Pipes		10	1.5 kg	30%	2.0 kg
VCHP	0.2 kg	10	1.5 kg	30%	2.0 kg
RHU's	0.1 kg	12	1.2 kg	30%	1.6 kg

New Frontiers Relay Submersible Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Landed Mass			**226.6 kg**	**43%**	**324.0 kg**
Stack (w/ Wet Element)			**226.6 kg**	**43%**	**324.0 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**226.6 kg**	**43%**	**324.0 kg**
Carried Elements			**0.0 kg**	**0%**	**0.0 kg**
Submersible Mass			**226.6 kg**	**43%**	**324.0 kg**
Wet Element			**226.6 kg**	**43%**	**324.0 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**226.6 kg**	**43%**	**324.0 kg**
System Contingency			**34.4 kg**	**15%**	
Subsystem Heritage Contingency			**63.0 kg**	**28%**	
Payload			**31.3 kg**	**30%**	**40.7 kg**
Instruments		**4**	**31.3 kg**	**30%**	**40.7 kg**
Hi rez GC-GC MS	25.0 kg	1	25.0 kg	30%	32.5 kg
FTIR spectrometer	2.0 kg	1	2.0 kg	30%	2.6 kg
LPP instruments	4.0 kg	1	4.0 kg	30%	5.2 kg
Descent camera	0.3 kg	1	0.3 kg	30%	0.4 kg
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**195.3 kg**	**27%**	**248.9 kg**
Attitude Control		**1**	**0.0 kg**	**0%**	**0.0 kg**
Command & Data		**4**	**2.8 kg**	**30%**	**3.7 kg**
Custom_Special_Function_Board: ETM - Sequencer/Inst I/F	0.7 kg	2	1.4 kg	30%	1.8 kg
Custom_Special_Function_Board: ETM - Radio I/F	0.7 kg	2	1.4 kg	30%	1.8 kg
Power		**13**	**31.8 kg**	**30%**	**41.3 kg**
Li-CFx (Primary Battery)	5.4 kg	4	21.6 kg	30%	28.1 kg
Chassis	1.8 kg	1	1.8 kg	30%	2.4 kg
Power Switch Cards (& ETM 3U card) - Load Switches Boards	0.9 kg	4	3.6 kg	30%	4.7 kg
Power Conditioning (& ETM 3U card) - Modeled as Houskeeping DC-DC Converters* Boards	1.1 kg	2	2.2 kg	30%	2.9 kg
Lander Power Interface Slice - Modeled as Power/Shunt Control* Boards	1.8 kg	1	1.8 kg	30%	2.3 kg
Shielding	0.8 kg	1	0.8 kg	30%	1.0 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**12**	**123.8 kg**	**30%**	**160.9 kg**
Struc. & Mech.		11	104.0 kg	30%	135.3 kg
Internal Primary Structure	13.5 kg	1	13.5 kg	30%	17.5 kg
Secondary Structure	4.1 kg	1	4.1 kg	30%	5.4 kg
Hull (0.7 m Spherical Pressure Vessel)	20.9 kg	2	41.8 kg	30%	54.3 kg
Module Connector	10.0 kg	1	10.0 kg	30%	13.0 kg
Sink Rate Controller	6.0 kg	1	6.0 kg	30%	7.8 kg
Module Separation System	3.2 kg	1	3.2 kg	30%	4.2 kg
Solid Sampling Tool	12.5 kg	1	12.5 kg	30%	16.3 kg
Initial Bouyancy Device	6.0 kg	2	12.0 kg	30%	15.6 kg
Integration Hardware	0.9 kg	1	0.9 kg	30%	1.2 kg
Cabling Harness	19.7 kg	1	19.7 kg	30%	25.7 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Telecom		**24**	**16.1 kg**	**0%**	**16.1 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	0%	0.3 kg
UST (Single Band)	3.5 kg	2	7.0 kg	0%	7.0 kg
X-band SSPA, RF=15W*	1.5 kg	2	3.0 kg	0%	3.0 kg
Hybrid Coupler	0.0 kg	1	0.0 kg	0%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	0%	0.7 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	1	0.4 kg	0%	0.4 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	0%	0.1 kg
Coax Cable, flex (190)	0.2 kg	8	1.3 kg	0%	1.3 kg
WR-112 WG, rigid (Al)	0.6 kg	6	3.3 kg	0%	3.3 kg
Thermal		**134**	**20.7 kg**	**29%**	**26.8 kg**
Multilayer Insulation (MLI)	0.4 kg	10	3.8 kg	30%	4.9 kg
Thermal Surfaces		1	0.1 kg	30%	0.1 kg
General	0.1 kg	1	0.1 kg	30%	0.1 kg
Thermal Conduction Control		11	2.1 kg	30%	2.7 kg
General	0.1 kg	1	0.1 kg	30%	0.1 kg
High Conductance	0.2 kg	10	2.0 kg	30%	2.6 kg
Temperature Sensors		50	0.8 kg	15%	0.9 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
PRT's	0.0 kg	25	0.3 kg	15%	0.3 kg
Thermal Switch	1.0 kg	2	2.0 kg	30%	2.6 kg
RHU's	0.4 kg	20	8.0 kg	30%	10.4 kg
Other Components		40	4.0 kg	30%	5.2 kg
Vacuum Getters	0.1 kg	40	4.0 kg	30%	5.2 kg

New Frontiers Relay Submersible Entry System Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Entry Mass			**550.6 kg**	**18%**	**648.1 kg**
Stack (w/ Wet Element)			**550.6 kg**	**18%**	**648.1 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**550.6 kg**	**18%**	**648.1 kg**
Carried Elements			**324.0 kg**	**0%**	**324.0 kg**
Submersible Mass			324.0 kg	0%	324.0 kg
Entry System Mass			**226.6 kg**	**43%**	**324.1 kg**
Wet Element			**226.6 kg**	**43%**	**324.1 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**226.6 kg**	**43%**	**324.1 kg**
System Contingency			**29.9 kg**	**13%**	
Subsystem Heritage Contingency			**67.6 kg**	**30%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**226.6 kg**	**30%**	**294.2 kg**
Attitude Control		**4**	**0.3 kg**	**10%**	**0.4 kg**
Accelerometers	0.1 kg	4	0.3 kg	10%	0.4 kg
Command & Data		**0**	**0.0 kg**	**0%**	**0.0 kg**
Power		**11**	**12.6 kg**	**30%**	**16.3 kg**
Li-SOCl2 (Primary Battery)	2.3 kg	3	6.9 kg	30%	9.0 kg
Thermal Battery (Thermal Battery)	1.1 kg	3	3.4 kg	30%	4.4 kg
Chassis	0.7 kg	1	0.7 kg	30%	0.9 kg
Power and Battery Interface - Load Switches Boards	0.4 kg	1	0.4 kg	30%	0.5 kg
Pyro Switches* Boards	0.5 kg	2	1.0 kg	30%	1.3 kg
Shielding	0.1 kg	1	0.1 kg	30%	0.2 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**4**	**182.8 kg**	**30%**	**237.6 kg**
Struc. & Mech.		3	177.2 kg	30%	230.3 kg
Heatshield and Backshell	135.6 kg	1	135.6 kg	30%	176.3 kg
Parachute	39.3 kg	1	39.3 kg	30%	51.1 kg
Balance Mass	2.3 kg	1	2.3 kg	30%	2.9 kg
Cabling Harness	5.6 kg	1	5.6 kg	30%	7.3 kg
Telecom		**2**	**1.0 kg**	**0%**	**1.0 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	0%	0.3 kg
WR-112 WG, rigid (Al)	0.7 kg	1	0.7 kg	0%	0.7 kg
Thermal		**107**	**30.0 kg**	**30%**	**38.9 kg**
Multilayer Insulation (MLI)	1.5 kg	16	24.0 kg	30%	31.2 kg
Thermal Surfaces		15	0.4 kg	30%	0.5 kg
General	0.0 kg	15	0.4 kg	30%	0.5 kg
Thermal Conduction Control		1	0.1 kg	30%	0.1 kg
General	0.1 kg	1	0.1 kg	30%	0.1 kg
Temperature Sensors		25	0.5 kg	15%	0.6 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
RHU's	0.1 kg	50	5.0 kg	30%	6.5 kg

New Frontiers Relay Submersible Cruise Stage Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Launch Mass			**1845.3 kg**	**6%**	**2058.4 kg**
Launch Vehicle PLA			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Wet Element)			**1845.3 kg**	**12%**	**2058.4 kg**
Useable Propellant			**654.4 kg**	**0%**	**654.4 kg**
Stack (w/ Dry Element)			**1191.0 kg**	**18%**	**1404.1 kg**
Carried Elements			**648.1 kg**	**0%**	**648.1 kg**
Entry System and Submersible			648.1 kg	0%	648.1 kg
Carrier Stage Mass			**542.9 kg**	**39%**	**756.0 kg**
Wet Element			**1197.3 kg**	**18%**	**1410.4 kg**
Useable Propellant			**654.4 kg**	**0%**	**654.4 kg**
System 1: Monoprop			**654.4 kg**	**0%**	**654.4 kg**
Dry Element			**542.9 kg**	**39%**	**756.0 kg**
System Contingency			**104.3 kg**	**23%**	
Subsystem Heritage Contingency			**108.8 kg**	**20%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**542.9 kg**	**20%**	**651.7 kg**
Attitude Control		**8**	**5.4 kg**	**24%**	**6.7 kg**
Sun Sensors	0.1 kg	3.0	0.2 kg	30%	0.2 kg
Star Trackers	1.5 kg	2.0	3.0 kg	30%	3.8 kg
IMUs	0.8 kg	2.0	1.5 kg	10%	1.7 kg
Shielding:	0.8 kg	1.0	0.8 kg	30%	1.0 kg
Command & Data		**18**	**17.6 kg**	**16%**	**20.5 kg**
Processor: RAD750	0.6 kg	2	1.1 kg	5%	1.2 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg	5%	1.5 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg	5%	1.5 kg
General_I_F: MSIA	0.7 kg	2	1.4 kg	5%	1.5 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg	17%	1.5 kg
Power: CEPCU	1.2 kg	2	2.3 kg	10%	2.5 kg
Backplane: CPCI backplane (6 slots)	0.6 kg	2	1.2 kg	30%	1.6 kg
Chassis: CDH chassis (6 slot)	2.9 kg	2	5.7 kg	30%	7.4 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg	6%	1.7 kg
Power		**16**	**77.3 kg**	**30%**	**100.5 kg**
Advanced Li-Ion (Secondary Battery)	5.9 kg	3	17.8 kg	30%	23.1 kg
Advanced Stirling (ASRG-850C)	22.0 kg	2	44.0 kg	30%	57.1 kg
Chassis	6.0 kg	1	6.0 kg	30%	7.8 kg
Power Switching - Modeled as Load Switches Boards	0.9 kg	3	2.7 kg	30%	3.5 kg
GID - Modeled as Thruster Drivers* Boards	0.8 kg	1	0.8 kg	30%	1.0 kg
Power Conditioning - Modeled as Houskeeping DC-DC Converters* Boards	1.1 kg	1	1.1 kg	30%	1.4 kg
Power bus and shunt control - Modeled as Power/Shunt Control* Boards	1.1 kg	1	1.1 kg	30%	1.4 kg
ARPS (Stirling) Controller* Boards	0.8 kg	2	1.6 kg	30%	2.1 kg
Power junction box - Modeled as Diodes* Boards	1.4 kg	1	1.4 kg	30%	1.8 kg
Shielding	0.9 kg	1	0.9 kg	30%	1.2 kg
Propulsion		**74**	**150.0 kg**	**2%**	**153.5 kg**
System 1: Monoprop		74	150.0 kg	2%	153.5 kg
Hardware		74	102.7 kg	3%	106.2 kg
Gas Service Valve	0.2 kg	2	0.5 kg	2%	0.5 kg
LP Transducer	0.3 kg	2	0.5 kg	2%	0.6 kg
Temp. Sensor	0.0 kg	2	0.0 kg	2%	0.0 kg
Liq. Service Valve	0.3 kg	1	0.3 kg	2%	0.3 kg
Liq. Filter	0.5 kg	1	0.5 kg	2%	0.5 kg
LP Latch Valve	0.4 kg	4	1.4 kg	2%	1.4 kg
Temp. Sensor	0.0 kg	14	0.1 kg	2%	0.1 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Lines, Fittings, Misc.	0.1 kg	30	3.0 kg	50%	4.5 kg
Monoprop Main Engine	0.9 kg	4	3.5 kg	2%	3.6 kg
Monoprop Thrusters 1	0.3 kg	12	4.0 kg	2%	4.0 kg
Fuel Tanks	44.5 kg	2	88.9 kg	2%	90.7 kg
Pressurant			1.5 kg	0%	1.5 kg
Residuals			45.8 kg	0%	45.8 kg
Mechanical		**5**	**186.6 kg**	**30%**	**242.6 kg**
Struc. & Mech.		3	151.0 kg	30%	196.3 kg
Primary Structure	133.3 kg	1	133.3 kg	30%	173.3 kg
Secondary Structure	8.4 kg	1	8.4 kg	30%	10.9 kg
Integration Hardware	9.3 kg	1	9.3 kg	30%	12.1 kg
Adapter, Spacecraft side	14.0 kg	1	14.0 kg	30%	18.2 kg
Cabling Harness	21.6 kg	1	21.6 kg	30%	28.0 kg
Telecom		**44**	**64.2 kg**	**16%**	**74.4 kg**
X/Ka-HGA 3.0m diam Parabolic High Gain Antenna	33.7 kg	1	33.7 kg	15%	38.8 kg
X-MGA (19dB) MER	0.6 kg	1	0.6 kg	10%	0.7 kg
X-LGA	0.5 kg	2	0.9 kg	10%	1.0 kg
UST (Dual Band)	4.5 kg	2	9.0 kg	20%	10.8 kg
X-band SSPA, RF=15W*	1.5 kg	2	3.0 kg	10%	3.3 kg
Ka-band TWTA, RF<100W	2.9 kg	2	5.8 kg	10%	6.4 kg
Hybrid Coupler	0.0 kg	2	0.0 kg	10%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	10%	0.8 kg
Ka-band Isolator	0.5 kg	2	1.0 kg	10%	1.1 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	4	1.5 kg	10%	1.7 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	10%	0.1 kg
Coax Cable, flex (190)	0.2 kg	12	2.0 kg	25%	2.5 kg
WR-112 WG, rigid (Al)	0.7 kg	8	5.4 kg	25%	6.7 kg
WR-28 WG, rigid (Al)	0.2 kg	3	0.5 kg	25%	0.7 kg
Thermal		**251**	**41.9 kg**	**28%**	**53.7 kg**
Multilayer Insulation (MLI)	0.8 kg	41	31.0 kg	30%	40.3 kg
Thermal Surfaces		28	0.7 kg	30%	0.9 kg
General	0.0 kg	28	0.7 kg	30%	0.9 kg
Thermal Conduction Control		4	0.8 kg	30%	1.0 kg
General	0.8 kg	1	0.8 kg	30%	1.0 kg
Isolation (G-10)	0.0 kg	3	0.0 kg	30%	0.0 kg
Heaters		34	2.4 kg	13%	2.7 kg
Custom	0.1 kg	20	1.0 kg	30%	1.3 kg
Propulsion Tank Heaters	0.1 kg	8	0.8 kg	0%	0.8 kg
Propulsion Line Heaters	0.1 kg	6	0.6 kg	0%	0.6 kg
Temperature Sensors		100	2.0 kg	15%	2.3 kg
Thermistors	0.0 kg	100	2.0 kg	15%	2.3 kg
Thermostats		20	0.4 kg	15%	0.5 kg
Mechanical	0.0 kg	20	0.4 kg	15%	0.5 kg
Thermal Louvers	1.0 kg	2	2.0 kg	30%	2.5 kg
Heat Pipes		10	1.5 kg	30%	2.0 kg
VCHP	0.2 kg	10	1.5 kg	30%	2.0 kg
RHU's	0.1 kg	12	1.2 kg	30%	1.6 kg

New Frontiers Relay Floating Lander Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Landed Mass			**167.8 kg**	**45%**	**243.7 kg**
Stack (w/ Wet Element)			**167.8 kg**	**45%**	**243.7 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**167.8 kg**	**45%**	**243.7 kg**
Carried Elements			**0.0 kg**	**0%**	**0.0 kg**
Floating Lander Mass			**167.8 kg**	**45%**	**243.7 kg**
Wet Element			**167.8 kg**	**45%**	**243.7 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**167.8 kg**	**45%**	**243.7 kg**
System Contingency			**30.5 kg**	**16%**	
Subsystem Heritage Contingency			**54.1 kg**	**27%**	
Payload			**29.3 kg**	**30%**	**38.1 kg**
Instruments		**3**	**29.3 kg**	**30%**	**38.1 kg**
Low rez GC-GC MS	25.0 kg	1	25.0 kg	30%	32.5 kg
LPP instruments	4.0 kg	1	4.0 kg	30%	5.2 kg
Descent camera	0.3 kg	1	0.3 kg	30%	0.4 kg
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**138.5 kg**	**26%**	**175.1 kg**
Attitude Control		**1**	**0.0 kg**	**0%**	**0.0 kg**
Command & Data		**4**	**2.8 kg**	**30%**	**3.7 kg**
Custom_Special_Function_Board: ETM - Sequencer/Inst I/F	0.7 kg	2	1.4 kg	30%	1.8 kg
Custom_Special_Function_Board: ETM - Radio I/F	0.7 kg	2	1.4 kg	30%	1.8 kg
Power		**16**	**26.4 kg**	**30%**	**34.3 kg**
Li-CFx (Primary Battery)	5.4 kg	3	16.2 kg	30%	21.0 kg
Chassis	1.8 kg	1	1.8 kg	30%	2.4 kg
Power Switch Cards (& ETM 3U card) - Load Switches Boards	0.9 kg	4	3.6 kg	30%	4.7 kg
Power Conditioning (& ETM 3U card) - Modeled as Houskeeping DC-DC Converters* Boards	1.1 kg	2	2.2 kg	30%	2.9 kg
Lander Power Interface Slice - Modeled as Power/Shunt Control* Boards	1.8 kg	1	1.8 kg	30%	2.3 kg
Shielding	0.8 kg	1	0.8 kg	30%	1.0 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**5**	**72.4 kg**	**30%**	**94.2 kg**
Struc. & Mech.		4	62.1 kg	30%	80.7 kg
Primary Structure	16.8 kg	1	16.8 kg	30%	21.8 kg
Secondary Structure	4.1 kg	1	4.1 kg	30%	5.4 kg
Hull	40.0 kg	1	40.0 kg	30%	52.0 kg
Integration Hardware	1.2 kg	1	1.2 kg	30%	1.5 kg
Cabling Harness	10.4 kg	1	10.4 kg	30%	13.5 kg
Telecom		**24**	**16.1 kg**	**0%**	**16.1 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	0%	0.3 kg
UST (Single Band)	3.5 kg	2	7.0 kg	0%	7.0 kg
X-band SSPA, RF=15W*	1.5 kg	2	3.0 kg	0%	3.0 kg
Hybrid Coupler	0.0 kg	1	0.0 kg	0%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	0%	0.7 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	1	0.4 kg	0%	0.4 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	0%	0.1 kg
Coax Cable, flex (190)	0.2 kg	8	1.3 kg	0%	1.3 kg
WR-112 WG, rigid (Al)	0.6 kg	6	3.3 kg	0%	3.3 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Thermal		**134**	**20.7 kg**	**29%**	**26.8 kg**
Multilayer Insulation (MLI)	0.4 kg	10	3.8 kg	30%	4.9 kg
Thermal Surfaces		1	0.1 kg	30%	0.1 kg
General	0.1 kg	1	0.1 kg	30%	0.1 kg
Thermal Conduction Control		11	2.1 kg	30%	2.7 kg
General	0.1 kg	1	0.1 kg	30%	0.1 kg
High Conductance	0.2 kg	10	2.0 kg	30%	2.6 kg
Temperature Sensors		50	0.8 kg	15%	0.9 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
PRT's	0.0 kg	25	0.3 kg	15%	0.3 kg
Thermal Switch	1.0 kg	2	2.0 kg	30%	2.6 kg
RHU's	0.4 kg	20	8.0 kg	30%	10.4 kg
Other Components		40	4.0 kg	30%	5.2 kg
Vacuum Getter	0.1 kg	40	4.0 kg	30%	5.2 kg

New Frontiers Relay Floating Lander Entry System Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Entry Mass			**396.0 kg**	**17%**	**461.5 kg**
Stack (w/ Wet Element)			**396.0 kg**	**17%**	**461.5 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Dry Element)			**396.0 kg**	**17%**	**461.5 kg**
Carried Elements			**243.7 kg**	**0%**	**243.7 kg**
Floating Lander			243.7 kg	0%	243.7 kg
Entry System Mass			**152.3 kg**	**43%**	**217.8 kg**
Wet Element			**152.3 kg**	**43%**	**217.8 kg**
Useable Propellant			**0.0 kg**	**0%**	**0.0 kg**
Dry Element			**152.3 kg**	**43%**	**217.8 kg**
System Contingency			**20.2 kg**	**13%**	
Subsystem Heritage Contingency			**45.3 kg**	**30%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**152.3 kg**	**30%**	**197.6 kg**
Attitude Control		**5**	**0.3 kg**	**10%**	**0.4 kg**
Accelerometers	0.1 kg	4.0	0.3 kg	10%	0.4 kg
Command & Data		**0**	**0.0 kg**	**0%**	**0.0 kg**
Power		**11**	**12.6 kg**	**30%**	**16.3 kg**
Li-SOCl2 (Primary Battery)	2.3 kg	3	6.9 kg	30%	9.0 kg
Thermal Battery (Thermal Battery)	1.1 kg	3	3.4 kg	30%	4.4 kg
Chassis	0.7 kg	1	0.7 kg	30%	0.9 kg
Power and Battery Interface - Load Switches Boards	0.4 kg	1	0.4 kg	30%	0.5 kg
Pyro Switches* Boards	0.5 kg	2	1.0 kg	30%	1.3 kg
Shielding	0.1 kg	1	0.1 kg	30%	0.2 kg
Propulsion		**0**	**0.0 kg**	**0%**	**0.0 kg**
Mechanical		**5**	**125.1 kg**	**30%**	**162.6 kg**
Struc. & Mech.		4	120.5 kg	30%	156.6 kg
Heatshield and Backshell	84.1 kg	1	84.1 kg	30%	109.3 kg
Parachute	24.4 kg	1	24.4 kg	30%	31.7 kg
Integration Hardware	10.5 kg	1	10.5 kg	30%	13.7 kg
Balance Mass	1.5 kg	1	1.5 kg	30%	2.0 kg
Cabling Harness	4.6 kg	1	4.6 kg	30%	6.0 kg
Telecom		**2**	**1.0 kg**	**0%**	**1.0 kg**
X-LGA Patch (3 to 6dB)	0.3 kg	1	0.3 kg	0%	0.3 kg
WR-112 WG, rigid (Al)	0.7 kg	1	0.7 kg	0%	0.7 kg
Thermal		**77**	**13.4 kg**	**29%**	**17.3 kg**
Multilayer Insulation (MLI)	0.7 kg	16	10.4 kg	30%	13.5 kg
Thermal Surfaces		15	0.4 kg	30%	0.5 kg
General	0.0 kg	15	0.4 kg	30%	0.5 kg
Thermal Conduction Control		1	0.1 kg	30%	0.1 kg
General	0.1 kg	1	0.1 kg	30%	0.1 kg
Temperature Sensors		25	0.5 kg	15%	0.6 kg
Thermistors	0.0 kg	25	0.5 kg	15%	0.6 kg
RHU's	0.1 kg	20	2.0 kg	30%	2.6 kg

New Frontiers Relay Floating Lander Cruise Stage Master Equipment List

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Total Launch Mass			**1416.2 kg**	**6%**	**1604.5 kg**
Launch Vehicle PLA			**0.0 kg**	**0%**	**0.0 kg**
Stack (w/ Wet Element)			**1416.2 kg**	**13%**	**1604.5 kg**
Useable Propellant			**482.0 kg**	**0%**	**482.0 kg**
Stack (w/ Dry Element)			**934.2 kg**	**20%**	**1122.6 kg**
Carried Elements			**461.5 kg**	**0%**	**461.5 kg**
Entry System and Floating Lander			461.5 kg	0%	461.5 kg
Carrier Stage Mass			**472.7 kg**	**40%**	**661.0 kg**
Wet Element			**954.7 kg**	**20%**	**1143.0 kg**
Useable Propellant			**482.0 kg**	**0%**	**482.0 kg**
System 1: Monoprop			**482.0 kg**	**0%**	**482.0 kg**
Dry Element			**472.7 kg**	**40%**	**661.0 kg**
System Contingency			**91.3 kg**	**22%**	
Subsystem Heritage Contingency			**97.1 kg**	**21%**	
Payload			**0.0 kg**	**0%**	**0.0 kg**
Instruments		**0**	**0.0 kg**	**0%**	**0.0 kg**
Additional Payload		**0**	**0.0 kg**	**0%**	**0.0 kg**
Bus			**472.7 kg**	**21%**	**569.8 kg**
Attitude Control		**8**	**5.4 kg**	**24%**	**6.7 kg**
Sun Sensors	0.1 kg	3.0	0.2 kg	30%	0.2 kg
Star Trackers	1.5 kg	2.0	3.0 kg	30%	3.8 kg
IMUs	0.8 kg	2.0	1.5 kg	10%	1.7 kg
Shielding:	0.8 kg	1.0	0.8 kg	30%	1.0 kg
Command & Data		**18**	**17.6 kg**	**16%**	**20.5 kg**
Processor: RAD750	0.6 kg	2	1.1 kg	5%	1.2 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg	5%	1.5 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg	5%	1.5 kg
General_I_F: MSIA	0.7 kg	2	1.4 kg	5%	1.5 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg	17%	1.5 kg
Power: CEPCU	1.2 kg	2	2.3 kg	10%	2.5 kg
Backplane: CPCI backplane (6 slots)	0.6 kg	2	1.2 kg	30%	1.6 kg
Chassis: CDH chassis (6 slot)	2.9 kg	2	5.7 kg	30%	7.4 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg	6%	1.7 kg
Power		**15**	**68.4 kg**	**30%**	**88.9 kg**
Advanced Li-Ion (Secondary Battery)	4.4 kg	2	8.8 kg	30%	11.5 kg
Advanced Stirling (ASRG-850C)	22.0 kg	2	44.0 kg	30%	57.1 kg
Chassis	6.0 kg	1	6.0 kg	30%	7.8 kg
Power Switching - Modeled as Load Switches Boards	0.9 kg	3	2.7 kg	30%	3.5 kg
GID - Modeled as Thruster Drivers* Boards	0.8 kg	1	0.8 kg	30%	1.0 kg
Power Conditioning - Modeled as Houskeeping DC-DC Converters* Boards	1.1 kg	1	1.1 kg	30%	1.4 kg
Power bus and shunt control - Modeled as Power/Shunt Control* Boards	1.1 kg	1	1.1 kg	30%	1.4 kg
ARPS (Stirling) Controller* Boards	0.8 kg	2	1.6 kg	30%	2.1 kg
Power junction box - Modeled as Diodes* Boards	1.4 kg	1	1.4 kg	30%	1.8 kg
Shielding	0.9 kg	1	0.9 kg	30%	1.2 kg
Propulsion		**74**	**117.7 kg**	**3%**	**120.8 kg**
System 1: Monoprop		74	117.7 kg	3%	120.8 kg
Hardware		74	83.0 kg	4%	86.1 kg
Gas Service Valve	0.2 kg	2	0.5 kg	2%	0.5 kg
LP Transducer	0.3 kg	2	0.5 kg	2%	0.6 kg
Temp. Sensor	0.0 kg	2	0.0 kg	2%	0.0 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Liq. Service Valve	0.3 kg	1	0.3 kg	2%	0.3 kg
Liq. Filter	0.5 kg	1	0.5 kg	2%	0.5 kg
LP Latch Valve	0.4 kg	4	1.4 kg	2%	1.4 kg
Temp. Sensor	0.0 kg	14	0.1 kg	2%	0.1 kg
Lines, Fittings, Misc.	0.1 kg	30	3.0 kg	50%	4.5 kg
Monoprop Main Engine	0.9 kg	4	3.5 kg	2%	3.6 kg
Monoprop Thrusters 1	0.3 kg	12	4.0 kg	2%	4.0 kg
Fuel Tanks	34.6 kg	2	69.2 kg	2%	70.6 kg
Pressurant			1.0 kg	0%	1.0 kg
Residuals			33.7 kg	0%	33.7 kg
Mechanical		**5**	**162.0 kg**	**30%**	**210.6 kg**
Struc. & Mech.		3	129.7 kg	30%	168.6 kg
Primary Structure	114.2 kg	1	114.2 kg	30%	148.5 kg
Secondary Structure	7.5 kg	1	7.5 kg	30%	9.7 kg
Integration Hardware	8.0 kg	1	8.0 kg	30%	10.4 kg
Adapter, Spacecraft side	12.7 kg	1	12.7 kg	30%	16.5 kg
Cabling Harness	19.6 kg	1	19.6 kg	30%	25.5 kg
Telecom		**44**	**64.2 kg**	**16%**	**74.4 kg**
X/Ka-HGA 3.0m diam Parabolic High Gain Antenna	33.7 kg	1	33.7 kg	15%	38.8 kg
X-MGA (19dB) MER	0.6 kg	1	0.6 kg	10%	0.7 kg
X-LGA	0.5 kg	2	0.9 kg	10%	1.0 kg
UST (Dual Band)	4.5 kg	2	9.0 kg	20%	10.8 kg
X-band SSPA, RF=15W*	1.5 kg	2	3.0 kg	10%	3.3 kg
Ka-band TWTA, RF<100W	2.9 kg	2	5.8 kg	10%	6.4 kg
Hybrid Coupler	0.0 kg	2	0.0 kg	10%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	10%	0.8 kg
Ka-band Isolator	0.5 kg	2	1.0 kg	10%	1.1 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	4	1.5 kg	10%	1.7 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	10%	0.1 kg
Coax Cable, flex (190)	0.2 kg	12	2.0 kg	25%	2.5 kg
WR-112 WG, rigid (Al)	0.7 kg	8	5.4 kg	25%	6.7 kg
WR-28 WG, rigid (Al)	0.2 kg	3	0.5 kg	25%	0.7 kg
Thermal		**243**	**37.5 kg**	**28%**	**47.9 kg**
Multilayer Insulation (MLI)	0.8 kg	36	26.9 kg	30%	34.9 kg
Thermal Surfaces		25	0.6 kg	30%	0.8 kg
General	0.0 kg	25	0.6 kg	30%	0.8 kg
Thermal Conduction Control		4	0.5 kg	30%	0.7 kg
General	0.5 kg	1	0.5 kg	30%	0.7 kg
Isolation (G-10)	0.0 kg	3	0.0 kg	30%	0.0 kg
Heaters		34	2.4 kg	13%	2.7 kg
Custom	0.1 kg	20	1.0 kg	30%	1.3 kg
Propulsion Tank Heaters	0.1 kg	8	0.8 kg	0%	0.8 kg
Propulsion Line Heaters	0.1 kg	6	0.6 kg	0%	0.6 kg
Temperature Sensors		100	2.0 kg	15%	2.3 kg
Thermistors	0.0 kg	100	2.0 kg	15%	2.3 kg
Thermostats		20	0.4 kg	15%	0.5 kg
Mechanical	0.0 kg	20	0.4 kg	15%	0.5 kg
Thermal Louvers	1.0 kg	2	2.0 kg	30%	2.5 kg
Heat Pipes		10	1.5 kg	30%	2.0 kg
VCHP	0.2 kg	10	1.5 kg	30%	2.0 kg
RHU's	0.1 kg	12	1.2 kg	30%	1.6 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.	%-Unc. (% of CBE)	Predicted Basic Est.
Liq. Service Valve	0.3 kg	1	0.3 kg	2%	0.3 kg
Liq. Filter	0.5 kg	1	0.5 kg	2%	0.5 kg
LP Latch Valve	0.4 kg	4	1.4 kg	2%	1.4 kg
Temp. Sensor	0.0 kg	14	0.1 kg	2%	0.1 kg
Lines, Fittings, Misc.	0.1 kg	30	3.0 kg	50%	4.5 kg
Monoprop Main Engine	0.9 kg	4	3.5 kg	2%	3.6 kg
Monoprop Thrusters 1	0.3 kg	12	4.0 kg	2%	4.0 kg
Fuel Tanks	34.6 kg	2	69.2 kg	2%	70.6 kg
Pressurant			1.0 kg	0%	1.0 kg
Residuals			33.7 kg	0%	33.7 kg
Mechanical		**5**	**162.0 kg**	**30%**	**210.6 kg**
Struc. & Mech.		3	129.7 kg	30%	168.6 kg
Primary Structure	114.2 kg	1	114.2 kg	30%	148.5 kg
Secondary Structure	7.5 kg	1	7.5 kg	30%	9.7 kg
Integration Hardware	8.0 kg	1	8.0 kg	30%	10.4 kg
Adapter, Spacecraft side	12.7 kg	1	12.7 kg	30%	16.5 kg
Cabling Harness	19.6 kg	1	19.6 kg	30%	25.5 kg
Telecom		**44**	**64.2 kg**	**16%**	**74.4 kg**
X/Ka-HGA 3.0m diam Parabolic High Gain Antenna	33.7 kg	1	33.7 kg	15%	38.8 kg
X-MGA (19dB) MER	0.6 kg	1	0.6 kg	10%	0.7 kg
X-LGA	0.5 kg	2	0.9 kg	10%	1.0 kg
UST (Dual Band)	4.5 kg	2	9.0 kg	20%	10.8 kg
X-band SSPA, RF=15W*	1.5 kg	2	3.0 kg	10%	3.3 kg
Ka-band TWTA, RF<100W	2.9 kg	2	5.8 kg	10%	6.4 kg
Hybrid Coupler	0.0 kg	2	0.0 kg	10%	0.0 kg
X-band Diplexer, moderate isolation	0.4 kg	2	0.7 kg	10%	0.8 kg
Ka-band Isolator	0.5 kg	2	1.0 kg	10%	1.1 kg
Waveguide Transfer Switch (WGTS)	0.4 kg	4	1.5 kg	10%	1.7 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg	10%	0.1 kg
Coax Cable, flex (190)	0.2 kg	12	2.0 kg	25%	2.5 kg
WR-112 WG, rigid (Al)	0.7 kg	8	5.4 kg	25%	6.7 kg
WR-28 WG, rigid (Al)	0.2 kg	3	0.5 kg	25%	0.7 kg
Thermal		**243**	**37.5 kg**	**28%**	**47.9 kg**
Multilayer Insulation (MLI)	0.8 kg	36	26.9 kg	30%	34.9 kg
Thermal Surfaces		25	0.6 kg	30%	0.8 kg
General	0.0 kg	25	0.6 kg	30%	0.8 kg
Thermal Conduction Control		4	0.5 kg	30%	0.7 kg
General	0.5 kg	1	0.5 kg	30%	0.7 kg
Isolation (G-10)	0.0 kg	3	0.0 kg	30%	0.0 kg
Heaters		34	2.4 kg	13%	2.7 kg
Custom	0.1 kg	20	1.0 kg	30%	1.3 kg
Propulsion Tank Heaters	0.1 kg	8	0.8 kg	0%	0.8 kg
Propulsion Line Heaters	0.1 kg	6	0.6 kg	0%	0.6 kg
Temperature Sensors		100	2.0 kg	15%	2.3 kg
Thermistors	0.0 kg	100	2.0 kg	15%	2.3 kg
Thermostats		20	0.4 kg	15%	0.5 kg
Mechanical	0.0 kg	20	0.4 kg	15%	0.5 kg
Thermal Louvers	1.0 kg	2	2.0 kg	30%	2.5 kg
Heat Pipes		10	1.5 kg	30%	2.0 kg
VCHP	0.2 kg	10	1.5 kg	30%	2.0 kg
RHU's	0.1 kg	12	1.2 kg	30%	1.6 kg